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US Army Research Laboratory

Reassessing the Representative Heuristic of the Plywood Ballistic Mannequin Used in Live-Fire Testing

by Matthew B Kaufman and Linda LC Moss

NOTICES

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This endeavor addressed 2 efforts: 1) to determine if the materials of construction of the current plywood ballistic mannequin (or manikin) should be more closely controlled and 2) to revise the US Army Ballistic Research Laboratory plywood ballistic mannequin to more closely reflect the current US Army male population. Despite the changeability of materials of construction and design of the plywood ballistic mannequin, no previous US Army effort has ever been made to quantify this variability and its possible effect on live-fire testing analyses. The US Army Research Laboratory's Survivability/Lethality Analysis Directorate recommends a revised plywood ballistic mannequin be employed in future live-fire testing when US Army personnel vulnerability is to be assessed.

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Preface

This work was started in March 2014 and completed in December 2014. The use of either trade or manufacturers' names in this report does not constitute an official endorsement of any commercial products. This report may not be cited for purposes of advertisement.

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Executive Summary

This endeavor addressed 2 efforts: 1) to determine if the materials of construction of the current plywood ballistic mannequin (or manikin) should be more closely controlled and 2) to revise the US Army Ballistic Research Laboratory plywood ballistic mannequin to more closely reflect the current US Army male population.

The US Army Research Laboratory's Survivability/Lethality Analysis Directorate recommends a revised plywood ballistic mannequin be employed in future live-fire testing when US Army personnel vulnerability is to be assessed.

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1. Introduction

The representative (or representativeness) heuristic is a judgmental or decision-making shortcut. It is marked by the assumption that the data set of input variables is declared “representative”. When the data set is valid, this heuristic may result in the anecdotal fallacy, if the probability of the event is overstated. However, the more common flaw in this shortcut is when the data set is intuitively reasonable but invalid; then systemic error arises. This shortcut is employed by both engineers and analysts who lack sufficient data to make a decision or are weak in applied mathematics and unfamiliar with probabilism; they often fail to ensure their input data sets are valid. When the data set is invalid, this heuristic results in the “fallacy fallacy” (see Appendix A).

The representative heuristic is the common decision-making approach of employing a single case (i.e., a representative) from the population of possible inputs to generate a solution. That solution amongst the population of possible answers will have potential systemic errors and an unavoidable bias, and based on experience, engineers and scientists have learned to apply a sufficiently large design margin or safety factor to ensure a robust design. According to M Mahaffey, “It is not the purpose of modeling to design the system, but rather to generate data to motivate robust design decisions.”[1] So, amidst the systemic error, competing priorities, and uncertainties, how do the analysts ensure they are not nudging these robust design decisions in the wrong direction?

Therefore, the representative heuristic is not always appropriate for problem solving.

The US Army currently employs the representative heuristic for modeling, testing, and for analyzing ballistic vulnerability[2] and lethality (BVL). For ballistic lethality analyses, this systemic error and bias are often acceptable. The combat developer and weapon system designer are quite content to accept some serendipitous overkill to ensure a result; it increases their confidence that the weapon’s outcome will be as anticipated or more destructive.

Unfortunately, one engineer’s design margin to ensure a robust design is another engineer’s interfering excess. It is the lethality ballistic analysts and engineers who have led the efforts to develop and standardize the methodologies for the whole ballistic community. For susceptibility,[3] vulnerability, or survivability analyses, this same acceptable systemic error and bias are in opposition to their needs; the combat developer and system designer are not pleased to hear protective or defensive measures or survivability enhancements will work less than anticipated.[4]

The plywood ballistic mannequin is an example of the representative heuristic.

1.1 Material of Construction

The initial plywood ballistic mannequins were fabricated from 0.75-inch-thick Douglas fir marine-grade (7-ply) plywood; however, the materials of construction simply list, “¾" plywood, marine grade or equal.”[5]

According to the American Plywood Association-Engineered Wood Association, Douglas fir from trees grown in the states of Washington, Oregon, California, Idaho, Montana, Wyoming, and the Canadian provinces of Alberta and British Columbia is statistically stronger than Douglas fir from trees grown in Nevada, Utah, Colorado, Arizona, and New Mexico.[6,7]

Although plywood has been and is still used in live-fire testing (LFT), a variety of actual thicknesses, plies (e.g., 7-ply and 5-ply), wood species (e.g., Douglas fir, southern pine, birch), painted[8] and unpainted, have been used since 1975. These wood species have significantly different mechanical properties (see Appendix B). Failing to conduct calibration shots, the ballistic limit of the plywood, depending on its wood species, plies, etc., may be misstated, relative to the analytical standard the “Estimation of Striking Velocity from Wooden Manikin Assessment,”[9] which was based on WJ Bruchey’s 1975 study, *Estimation of the Striking and Residual Velocity of Fragments from Plywood Penetration*.[10]

Despite the changeability of materials of construction, no effort has ever been made in subsequent analyses to document or quantify this variability and its effect on LFT analyses. This is the first US Army effort to demonstrate whether this variability is relevant to its LFT analyses.

1.2 Mannequin Design

In support of the ballistic lethality evaluation of the M18 Claymore mines during 1950–52, the US Army Ballistic Research Laboratory (BRL) introduced a plywood ballistic mannequin for personnel vulnerability assessments (PVAs). The median stature of the Chinese infantryman of 1915 was reportedly 5 ft, 2 inches,[11,12] while the modern Chinese male’s median stature is approximately 5 ft, 6 inches.[13]

In 1979, in support of the ballistic lethality evaluation of the A10/GAU-8 weapon system and ammunition against 31 US M47 tanks, which were arranged in a static formation to simulate a Soviet main battle tank battalion, BRL used these same mannequins for PVA.[14] The average stature of the Russian male military recruit of 1924–28 was 5 ft, 6 inches, while the modern Russian male's stature is approximately 5 ft, 9.5 inches.[15]

Being shorter and smaller than the US Army male, the mannequin imparted a lethality bias when it was employed in the Bradley Fighting Vehicle[16] and subsequently in other US platforms.[17–19]

This mannequin—with subsequent modifications to make it shorter and smaller—has remained the "stake in the sand" for assessing ballistic vulnerability to all non-US and US personnel in LFT. Although this mannequin, according to its drawings (Appendix C), is 5 ft, 6 inches, in stature, plywood ballistic mannequins of other statures have been employed in LFT; the shorter plywood ballistic mannequins (3 to 6 inches shorter stature) are the direct result of reducing the height (and presented area) of the chest portion.[20]

Despite the mannequin's changeability and photographic documentation, no previous government effort has been made in subsequent analyses to highlight or quantify this variability and its possible effect on LFT analyses. This is the first US Army effort to resolve whether this variability is relevant to its LFT analyses.

1.3 Objective

The objective was 2-fold:

- Determine if the material of construction (i.e., plywood) needs to be more closely controlled by characterizing and evaluating the various species of plywood by the common measure of V_{50} ballistic limit, i.e., the velocity of plywood penetration with 50% probability.

- Modify the BRL plywood ballistic mannequin to better reflect the current US Army male population using the data sets and summaries from the 1988 and 2010 anthropometric surveys,[21,22] which were conducted by the US Army Natick Soldier Research, Development and Engineering Center.

2. Reassessing the Ballistic Limit of Plywood

The ballistic limit or limit velocity (V_{lim}) is the minimum velocity at which a particular ballistic projectile or fragment of a given mass, shape, and obliquity angle is expected to consistently perforate a barrier of a given material and thickness. It is also defined as the highest velocity that a predetermined threat will consistently be stopped by the barrier (armor). With the assumption that perforation is an increasing function of the velocity, there is an area between these 2 definitions that is the zone of mixed results, where the response is not consistent because the stochastic nature of apparently identical conditions that at times will produce a perforation and other times will get stopped. Thus, the ballistic is defined as the velocity at which 50% of the identical threats perforate the barrier under the same conditions.

2.1 Ballistic Limit via Direct Measurement

During the V_{50} ballistic limit testing, a modification of the Langlie sequential firing procedure[23] was used to obtain the desired velocities. Similar to the Up and Down Method, each subsequent shot is based on the partial penetration (PP, 0) or complete penetration (CP, 1) of the previous shot (or shots) in accordance with the firing procedure. A CP occurs when any portion of the threat perforates the plywood—that is, exits the plywood. A PP is any impact that is not a CP.

The procedure starts at an estimated V_{50} and continues between the predefined upper and lower projectile velocity limits (gates) until the "stopping rules" are met. The "stopping rules" include the criterion that the velocities of the 3 PPs and 3 CPs are within 125 ft/s. Typically, the criteria are met within 8 to 15 shots (see Appendix D for more details on the procedure).

Additional shots were taken at higher velocities to complete the residual velocity curve as a function of striking velocity. The goal is to have at least 10 shots per panel type that have a residual velocity of which approximately half of these would come from the ballistic limit test.

2.2 Ballistic Limit via Penetration Theory

The residual velocity of a penetrating fragment (e.g., sphere) through plywood is well understood and can be modeled, following the conservation of energy and momentum, by the following equations[24–26]:

$$V_r = \frac{\sqrt{V_s^2 - V_{50}^2}}{1 + \dfrac{\rho A_p T}{M \cos(\theta)}} \quad \text{and} \quad V_{50} = \left[\frac{2 L G_d T^2}{M \cos^2(\theta)} \right]^{0.5}, \tag{1}$$

where

G_d is the dynamic shear modulus of the plywood (Pa)[27];

L is the perimeter of the fragment's presented area (m);

M is the mass of the fragment (kg);

T is the thickness of the plywood (m);

V_{50} is the median ballistic velocity limit (m/s);

V_r is the residual velocity of the fragment (m/s);

V_s is the impacting velocity of the fragment (m/s);

ρ is the bulk density of the plywood (kg/m^3); and

Θ is the obliquity angle (degrees). For this study, Θ was set to zero.

Using Eq. 1, we numerically estimated 2 properties of the 0.75-inch-thick marine-grade plywood, which were employed in the Bruchey 1975 study: G_d was $3.68 \times 10^{+6}$ Pa (s.e., $6.7 \times 10^{+5}$ Pa), and ρ was 568 kg/m^3 (s.e., 32 kg/m^3).[28] The root-mean-square error for V_r was 28 m/s.[10]

2.3 Testing

Because of the cost of testing, only 6 different plywood sheets were considered, and only one penetrator was employed to assess the potential variability in penetrating velocities.

The varieties of plywood considered within this project are listed in Table 1. These species of plywood vary by their number of ply (e.g., 5, 7, and 11). See Appendix E for photographs of these plywood sheets.

A 16-gr, 0.64-cm-diameter steel sphere was selected for the ballistic testing: $L = 2.01 \times 10^{-2}$ m, and $M = 1.04 \times 10^{-3}$ kg. This ballistic challenge was selected because it was employed in the Bruchey 1975 study; its smaller size ensured the V_{50} might be measured more easily within the limitations of the gun barrel, and the sphere eliminated the concern of measuring the impact presented area. All shots were at 0° obliquity. Pre- and posttest mass, diameter, and velocity of the penetrator were measured and recorded.

Testing was conducted by the US Army Research Laboratory's (ARL's) System Engineering and Experimentation Branch, who also determined the areal density (kilograms per square meter) and bulk density (ρ, kilogram per cubic meter) of each plywood sheet. Wood samples were cut to approximately 12 by 12 inches, which produced 32 samples from each sheet. This allowed for 12–15 shots per sheet as part of the V_{50} ballistic limit testing and another 5–10 shots per sheet at higher velocities to construct a residual velocity curve as a function of striking velocity. Approximately 20 shots per full sheet were planned; a total of 143 shots were conducted.

Table 1 A summary of the testing of 0.75-inch-thick plywood sheets

Test Label	Plywood Description (Grade, Species, Ply)	Actual Thickness (T, m)	Areal density (kg/m^2)	Bulk Density (ρ, kg/m^3)	V_{lim}[a] (m/s) Calc. Value (Prob. Error)	V_{50}[a] (m/s) Exp.	Dynamic Shear Modulus (G_d, Pa)
	A/B, marine grade, Douglas fir, 7-ply	0.0190	10.8	568[b]	…	248[c]	$3.68\times10^{+6}$ [b]
1	A/B, marine grade, larch/fir, 7-ply[d]	0.0195	11.1	569	…	…	…
2	Vendor: John H Myers & Son Manufacturer: Potlatch Marine Corporation	0.0196	11.0	564	271 (27)	269	$4.97\times10^{+6}$
3	B/B, birch hardwood, 11-ply, veneer-core	0.0180	9.2	514	…	…	…
4	Vendor: John H Myers & Son Manufacturer: Georgia-Pacific, China	0.0182	9.4	514	239 (23)	236	$4.41\times10^{+6}$
5	CDX, yellow pine, 5-ply	0.0158	9.7	616	…	…	…
6	Vendor: John H Myers & Son Manufacturer: Georgia-Pacific	0.0158	9.9	624	234 (38)	231	$5.61\times10^{+6}$
7	A/B, marine-grade, Okoume, 11-ply	0.0188	10.3	547	…	…	…
8	Vendor: J Gibson McIlvain Company Manufacturer: Allin Bruynzeel	0.0188	10.1	535	249 (25)	249	$4.59\times10^{+6}$
9	A/B, marine-grade, Douglas fir, 7-ply	0.0191	10.1	532	…	…	…
10	Vendor: J Gibson McIlvain Company Manufacturer: Roseburg	0.0191	10.6	555	283 (30)	290	$6.00\times10^{+6}$
11	Painted A/B, marine-grade, Douglas fir, 7-ply	0.0194 [e]	9.9 [e]	509[e]	…	…	…
12	Vendor: J Gibson McIlvain Company Manufacturer: Roseburg	0.0193 [e]	9.9 [e]	514[e]	249 (35)	248	$4.34\times10^{+6}$

Notes: Calc = calculated value (and probable error) based on the impact (i.e., striking) and residual velocities data.
CDX = This is common construction plywood; CDX is often used in outdoor construction. Its level of plywood veneer is C/D, and it is only temporarily weather resistant (i.e., one exposure); its glue will not withstand rain or snow.
Exp = Experimentally determined values, using generalized linear models.[23]
[a]The penetrator was a 0.635-cm-diameter, 16-gr steel sphere.
[b]The values[28] in the green row are statistically derived from the test data reported by Bruchey.[10]
[c]This value is based on the penetration equation that was developed by Bruchey and is currently employed by the US Army Research Laboratory for estimating the striking velocity.[9] Bruchey reported an effective target density of 940 kg/m^3 when the empirical equation for estimation of the striking velocities, based on hole size, was determined via least squares analysis.
[d]Potlatch Corporation reports the materials of construction to be a combination of larch and Douglas fir, depending on the availability of each wood type.
[e]Measurement was made on unpainted plywood.

In addition to the striking (or impacting) velocity (V_s), the residual (or exiting) velocity (V_r) of the penetrating sphere was also captured using high-speed cameras along with a redundant chronograph.

The reported impact and residual velocities could be used to mathematically calculate the V_{lim} by extrapolating the fit to the y-axis and confirming the experimental estimate[23] for V_{50}. The dynamic shear modulus (G_d) could be estimated via the equation for V_{50} in Eq. 1. The results of this testing and analyses are summarized in Table 1 and Fig. 1. The individual plots of each plywood sheet are shown in Appendix F.

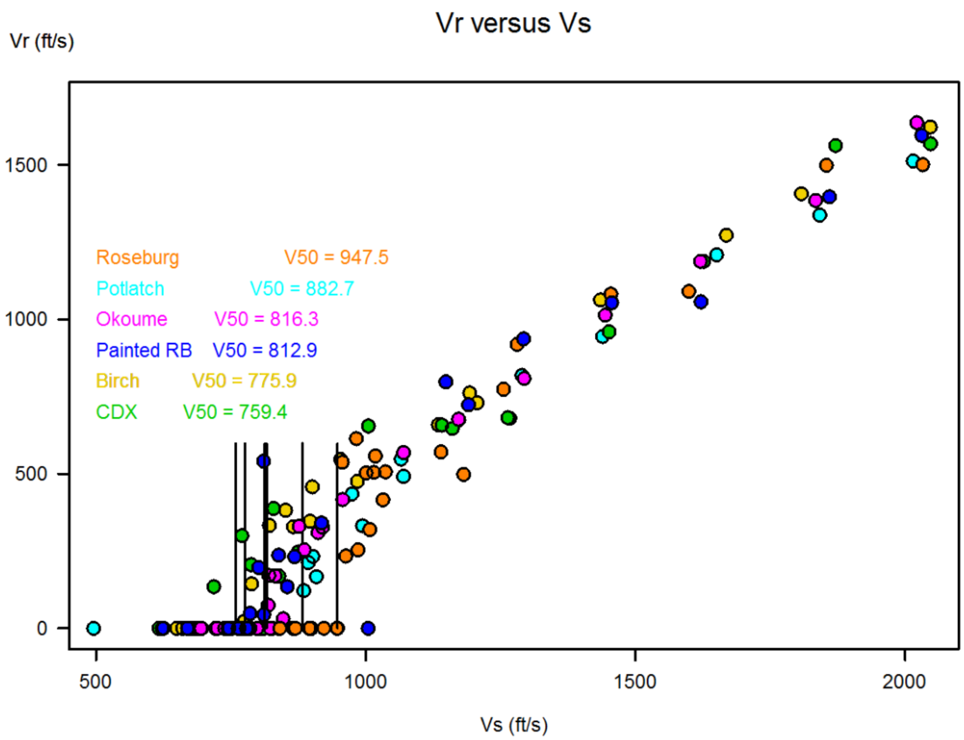

Fig. 1 A comparison of striking velocities (V_s, the horizontal axis) and residual velocities (V_r, the vertical axis) for the varieties of 0.75-inch-thick plywood sheets assessed by this report. Velocities are reported in units of feet per second.

Against the common penetrator (i.e., 16-gr, 0.64-cm-diameter steel sphere), the V_{50} was experimentally determined, and a comparison of the sampled plywood is pictorially shown (Fig. 2).

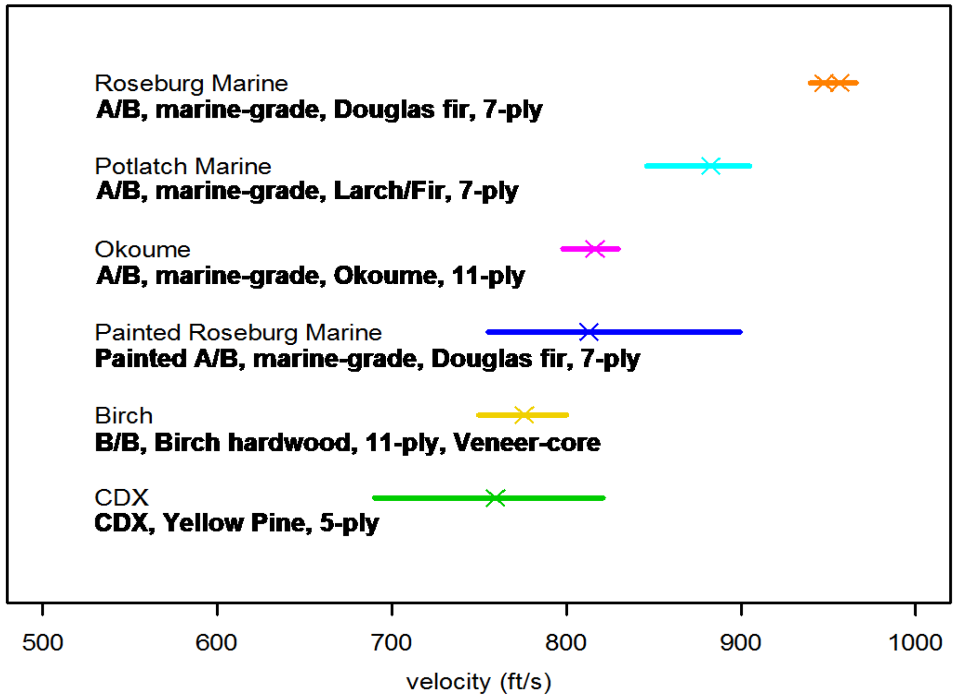

Fig. 2 A comparison of the V_{50} (with 90% confidence) for the various plywood samples. Velocities are reported in units of feet per second.

Based on Eq. 1, the V_{50} is expected to be dependent on the areal density. Fig. 3 provides a 2-dimensional comparison of test data of this study with the Bruchey 1975 report; only data for the 16-gr penetrator against nominal 0.75-inch-thick plywood are shown. Like Fig. 2, the V_{50} of plywood is scattered across the range of approximately 195 to 295 m/s (with 90% confidence). When only the data from marine-grade plywood sheets are considered and grouped together, the V_{50} is 264 m/s with a 90% confidence interval of 250 to 270 m/s.

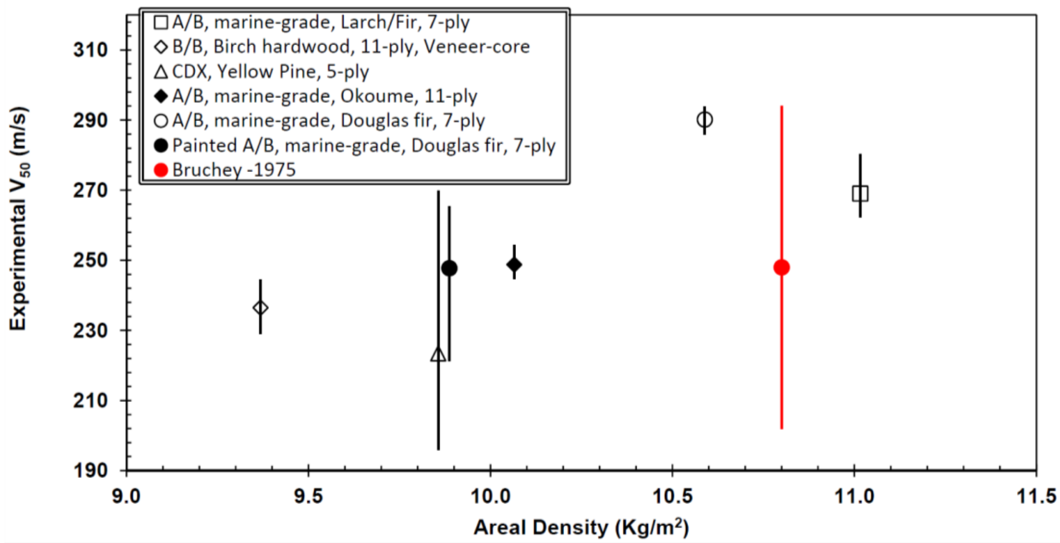

Fig. 3 A comparison of V_{50}'s (90% confidence interval) for the varieties of 0.75-inch plywood sheets assessed by report. Velocities are reported in units of meters per second.

However, the comparison of the plywood sheets (Fig. 3) may be inappropriate. Only the Bruchey data include the uncertainty of reliability (i.e., variability between plywood sheets). So, the confidence intervals of the plywood specimens would be expected to be larger with additional testing. The painted and unpainted A/B marine-grade Douglas fir (7-ply) plywood sheets are statistically different (i.e., there is a statistically significant difference between sheets of plywood of the same manufacturer, ply, and species). If the data from plywood specimen nos. 10 and no. 12 are combined, the 90% confidence interval for the V_{50} is 248 to 282 m/s.

The Eq. 2 has been rewritten to reflect the different nomenclature within this report

$$\mathrm{V}_{50} = (1.4054 \times 10^{+5}) \left[\frac{(\mathrm{L}^2)\mathrm{T}}{4\pi\mathrm{M}}\right]^{0.855}. \quad (2)$$

Although some of the plywood sheets' V_{50}'s are statistically different, across the narrow span of areal densities the V_{50} is only weakly dependent on areal density; the Pearson's correlation between V_{50} and the areal density was 0.804; with the Bruchey data included, the Pearson's correlation is reduced to 0.676. Cluster analysis (Fig. 4) of the squared Euclidean distances of the pair-wise comparisons of the p-values of the V_{50} data (see Appendix F, Table F-2) also supports an apparent dependence on areal density: the A/B marine-grade Douglas fir (7-ply) plywood is significantly different from the other sheets, but it is most similar to the A/B marine-grade larch fir (7-ply) plywood; and the A/B marine-grade larch fir (7-ply) plywood is significantly different from the other sheets.

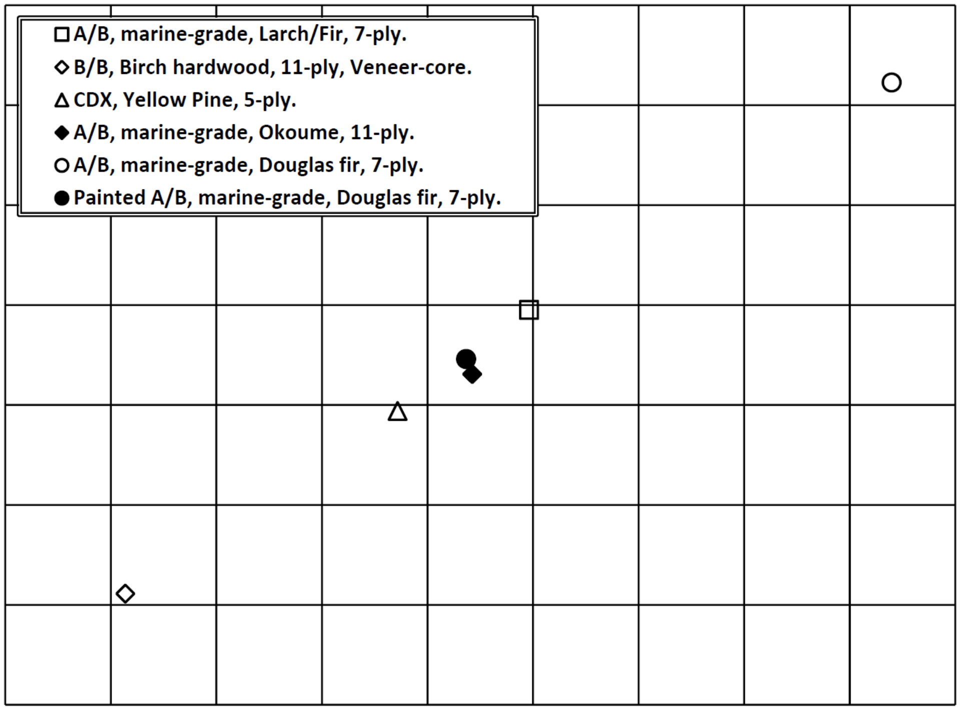

Fig. 4 **A data cluster analysis of the pair-wise comparisons of the response curves**

The significant difference observed between V_{50}'s of the unpainted and painted sheets of A/B marine-grade Douglas fir 7-ply (Roseburg) plywood cannot be attributed to the paint given the significant difference in areal density from sheet to sheet (9.9 and 10.6 kg/m^2, respectively). This indicates that the variation in estimates of V_{50} from sheet to sheet might be a greater problem for reliable testing and analyses than the specification of wood species, ply, thickness, etc.

A specification for a minimum-acceptable areal density rather than a more detailed description of materials might ensure a more reliable ballistic barrier. The tighter 90% confidence interval for the plywood with the greater areal densities suggests confidence might also be enhanced, too.

3. Reassessing the Mannequin's Design

The BRL plywood ballistic mannequin was a stake in the sand. The BRL plywood ballistic mannequin was not intended to represent the real US Army population when assessing hits, damage, or degradation to personnel during LFT. Its value was to provide a common standard for comparison to previous platforms; the presented areas of the mannequin and the location of those presented areas relative to the real population "were irrelevant."[29–33] However, that has not stopped more recent efforts to employ the plywood ballistic mannequin as a representative.

Formerly, the fragmentary hits to the plywood ballistic mannequins were analyzed for probability of incapacitation given a hit ($P_{I/H}$) of personnel using Kokinakis-Sperrazza equations,[34–37] which were based on human damage and degradation to the whole body or large body parts (e.g., head, arm, leg, pelvis, torso); new $P_{I/H}$ estimates were also derived using a ComputerMan[38–41]-based model (i.e., the Operational Requirement-based Casualty Assessment System, ORCA,[42,43] software suite). In this manner, the plywood mannequins were more accurately employed as "articulated witness plates"[14,44,45] rather than representatives of personnel.[46]

However, the stake in the sand was redefined as a representative of US Army personnel when the Survivability/Lethality Analysis Directorate (SLAD) desired to broaden the application and increase the use of its ORCA model.[47] SLAD had employed the representative heuristic. The ORCA model is currently used to determine specific hypothetical human damage and assess degradation by mapping the specific location of fragmentary hits to plywood to specific locations on the ComputerMan, despite their geometric differences and the diversity of the human population within a military platform (e.g., vehicle or airplane).

3.1 Revising the Plywood Ballistic Mannequin

The BRL plywood ballistic mannequin (Appendix C) was used as the template for the revised mannequin (Appendix G). Overall, the BRL plywood ballistic mannequin is shorter and smaller than the proposed ARL plywood ballistic mannequin (Fig. 5). The former has a frontal presented area of 0.491 m^2 and weighs approximately 25 lb, and the latter has a frontal presented area of 0.536 m^2 and weighs approximately 29 lb.[48]

Table 2 compares some basic anthropometric dimensions of the BRL and proposed ARL plywood ballistic mannequin. Table 3 and Fig. 6 compare the size of the presented areas of some of the components of the 2 mannequins. Presented area is a function of both size and location; therefore, this comparison of size is overly simplistic. Overall, the BRL plywood ballistic mannequin is smaller (by stature and presented area) than the proposed ARL plywood ballistic mannequin. Referring to Fig. 6, for those points that fall below the red line, the component of the proposed ARL mannequin is smaller than the component of the BRL mannequin; conversely, for those points that fall above the red line, the component of the proposed ARL mannequin is larger than the component of the BRL mannequin.

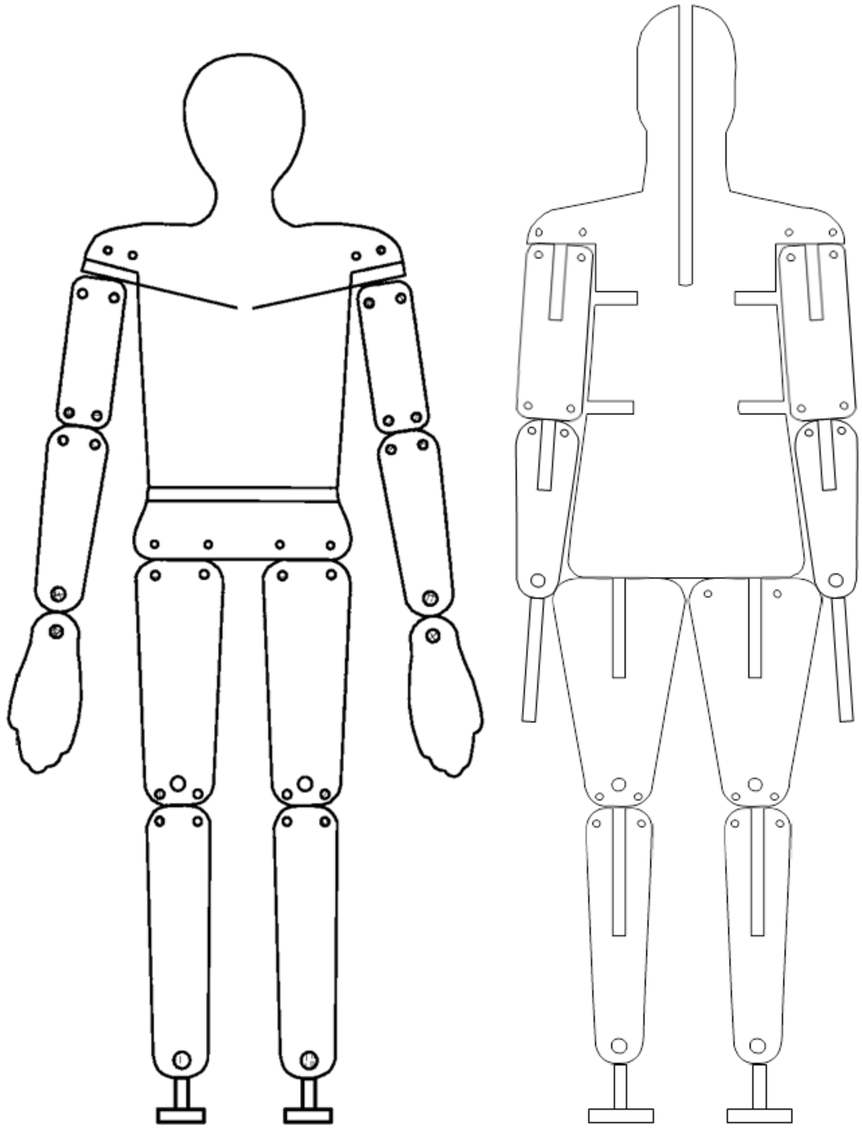

Fig. 5 The BRL (left) and the proposed ARL (right) plywood ballistic mannequins are side by side to show their components' respective sizes[49]

Table 2 A comparison of some anthropometric measurements of the BRL and the proposed ARL plywood ballistic mannequins

Anthropometry	Length (cm)	
	BRL	**ARL**
Acromial height	141.5	143.5
Bideltoid breadth	50.5	49.9
Chest breadth	34.0	28.5
Chest depth	26.7	24.6
Chest height, seated	62.2	45.7
Chest height, standing	140.3	129.3
Crotch height	90.0	85.5
Foot length	24.4[a]	27.1[b]
Functional grip reach	87.0	79.7
Functional leg length	101.3	114.4
Hand length	25.9	20.0
Head breadth	19.0	15.4
Head length	19.8	19.9
Hip breadth, seated	33.3	37.1
Midpatella	49.8	49.6
Pelvis breadth	33.3	37.1
Seated height	90.3	91.8
Stature	168.4	175.4
Thigh clearance, seated	18.3	17.8
Vertical grip reach down	78.8	72.5
Waist breadth	30.8	31.1
Waist depth	21.3	21.7
Waist height, seated	23.0	28.7
Waist height, standing	101.0	112.3

BRL = These dimensions reflect the BRL plywood ballistic mannequin (5-ft, 6-inch stature) (Appendix F).
ARL = These dimensions reflect the proposed ARL plywood ballistic mannequin (5-ft, 9-inch stature) (Appendix G).
[a]This is a US men's shoe size 7.
[b]This is a US men's shoe size 10.

Table 3 A comparison of the size of presented areas of some components of the BRL and the proposed ARL plywood ballistic mannequins

Component and View	Length (m^2)	
	BRL	**ARL**
Ankle (sagittal)	0.0080	0.0141
Calf (frontal)	0.0377	0.0363
Calf (sagittal)	0.0361	0.0379
Foot (caudal)	0.0153	0.0191
Foot (sagittal)	0.0145	0.0193
Forearm (frontal)	0.0245	0.0223
Forearm (sagittal)	0.0160	0.0161
Hand (frontal)	0.0049	0.0038
Hand (sagittal)	0.0218	0.0168
Head, torso, and pelvis (frontal)	0.2131	0.2370
Head, torso, and pelvis (sagittal)	0.1562	0.1865
- Head and neck only (frontal)	0.0242	0.0396
- Torso only (frontal)	0.1551	0.1062
- Pelvis only (frontal)	0.0338	0.0912
Thigh (frontal)	0.0491	0.0547
Thigh (sagittal)	0.0539	0.0684
Upper arm (frontal)	0.0192	0.0293
Upper arm (sagittal)	0.0126	0.0219

BRL = These dimensions reflect the BRL plywood ballistic mannequin (5-ft, 6-inch stature) (Appendix F).
ARL = These dimensions reflect the proposed ARL plywood ballistic mannequin (5-ft, 9-inch stature) (Appendix G).

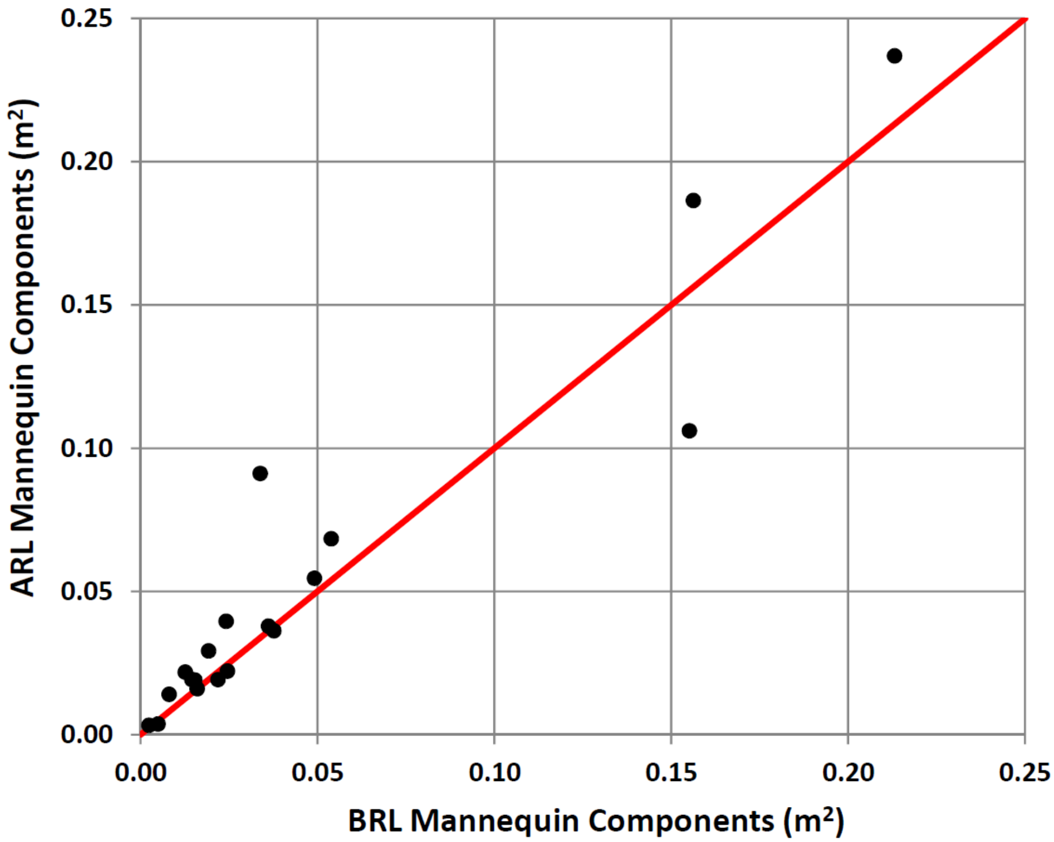

Fig. 6 A comparison of presented area of some components of the BRL and the proposed ARL plywood ballistic mannequins

The wider hips of the ARL plywood ballistic mannequin reflect the seated hip breadth to more accurately reflect PVA for seated application while producing some survivability bias in the standing or kneeling postures.

The ARL plywood ballistic mannequin has a strong chin, although such a feature cannot be statistically justified for a presented area. However, it is there to assist the tester to securely affix a helmet via a chin strap.

A simple mannequin, which can accommodate both the functional leg length and the crotch height (standing), is a compromise. For the BRL plywood ballistic mannequin, the hinge between the thigh and the torso is at the crotch of the plywood mannequin, while the actual hip joint is located several inches higher on human personnel. For this mannequin, functional leg length was probably sacrificed to more accurately preserve its stature and a crotch height (standing). Its data set of [stature, functional leg length, crotch height] (i.e., [168.4 cm, 101.3 cm, 90.0 cm]) is nonhuman. This mannequin best reflected a standing representative. In the seated position, the presented areas of the mannequin's thighs make up for the lacking presented area of its pelvis; this would have little effect on subsequent analyses if these presented areas were assessed collectively. However, the accuracy is sacrificed when the granularity is increased and the hits to the thighs and pelvis are segregated and assessed as hits to separate components (i.e., to the thigh and to the pelvis). Accuracy is further forfeited if this same mannequin is employed as a driver because of its unnaturally short functional leg length.

Relocating the hinge (between the thigh and the torso) forward of the frontal torso component to better accommodate both the functional leg length and the crotch height[4] requires a different compromise. Its wide flat base (i.e., the pelvis) forces the mannequin to sit a little high in any seat other than a bench seat (i.e., the seated height is increased), and each thigh component must be rotated 180° and exchanged with the opposite thigh component (depending on positioning).[50,51]

These 2 shortcomings are overcome by the proposed ARL plywood ballistic mannequin by relocating the hinges vertically between the crotch and waist, closer to where the natural hip joint would be located. This mannequin's wide pelvis reflects the median seated breadth and depth, but it will not sit as high as the aforementioned. The rectangular extension on the thigh components is not the presented area of the thigh but reflects the portion of the leg that is hidden within the pelvis. This ensures that any potential hits, which might have been registered by the thigh components of the BRL plywood ballistic mannequin, can be correctly identified as hits to the pelvis component.

3.2 Reassessing the Ballistic Mannequin

Employing the representative heuristic, anthropometric dimensions individually —and in isolation—may appear to be reasonable. However, the data set for the BRL mannequin is not always representative of the US Army males. Data cluster analyses, such as simple comparisons of 2 or more dimensions (Appendix H), can easily show that some physical dimensions of the ballistic mannequin are wrong, if the intent was to have a valid representative. This means that any analyses, based on principal component analysis (PCA) of the US Army anthropometric surveys, which employ the data set of the BRL mannequin, will be erroneous because of incorrectly inferring human degradation from the nonhuman nature of the plywood mannequin.

A single plywood mannequin that might be employed to be representative of the diverse human population is a compromise. The presented area of that population is a function of the presented area and the posture of the individuals of that population and the perspective of the observer. The length of the frontal presented area of the head of the standing population is slightly longer than the frontal presented area of the head of the same seated population; and the width of the sagittal presented area of the head of the standing population is slightly smaller than the sagittal presented area of the head of the same seated population. Therefore, the least biased, posture-independent, single plywood mannequin's design is one that is constructed based on the median values of major anthropometric dimensions.

The proposed ARL wooden ballistic mannequin is based on the median values of several major anthropometric dimensions. This approach also ensures its anthropometric data set falls well within the space of US Army male personnel. However, since it is a fabricated single representative, like the BRL mannequin, it too will impart a lethality bias by understating ballistic susceptibility, but this bias will not be as severe.

If any of the dimensions of the plywood ballistic mannequin are not representative of a human, when these dimensions define the location or size of a presented area, that location and/or presented area will not be representative of a human, either. As a result, any comparison between mannequins is a function of the posture and perspective of the comparison.

The least sensitive comparison is of the standing mannequins from the cranial or caudal view (i.e., from above or below). The second least sensitive comparison, although a very familiar one, is of the standing mannequins from a frontal or sagittal view (Fig. 7).

Since the dimensions and articulation of the plywood ballistic mannequins are not the same as a human, the presented areas of body components of the mannequins can be potentially positioned in the wrong locations, relative to the real population of personnel.

Therefore, the greater the mannequins are articulated, the greater the probability that they will be less representative of the US Army male population (Fig. 8). In both figures, any fragments' hits to the area of the BRL mannequin's torso will be disproportionately assigned to the chest and will underreport subsequent damage to the pelvis. As expected, Fig. 8 illustrates that the BRL mannequin deviates even more from the better representative. From the sagittal perspective of the seated mannequins, the smaller presented areas of the thigh and torso of the BRL plywood ballistic mannequin can be readily seen. Again, in this illustration, the BRL mannequin, relative to the proposed ARL mannequin, will underreport hits to the thigh, pelvis, and torso.

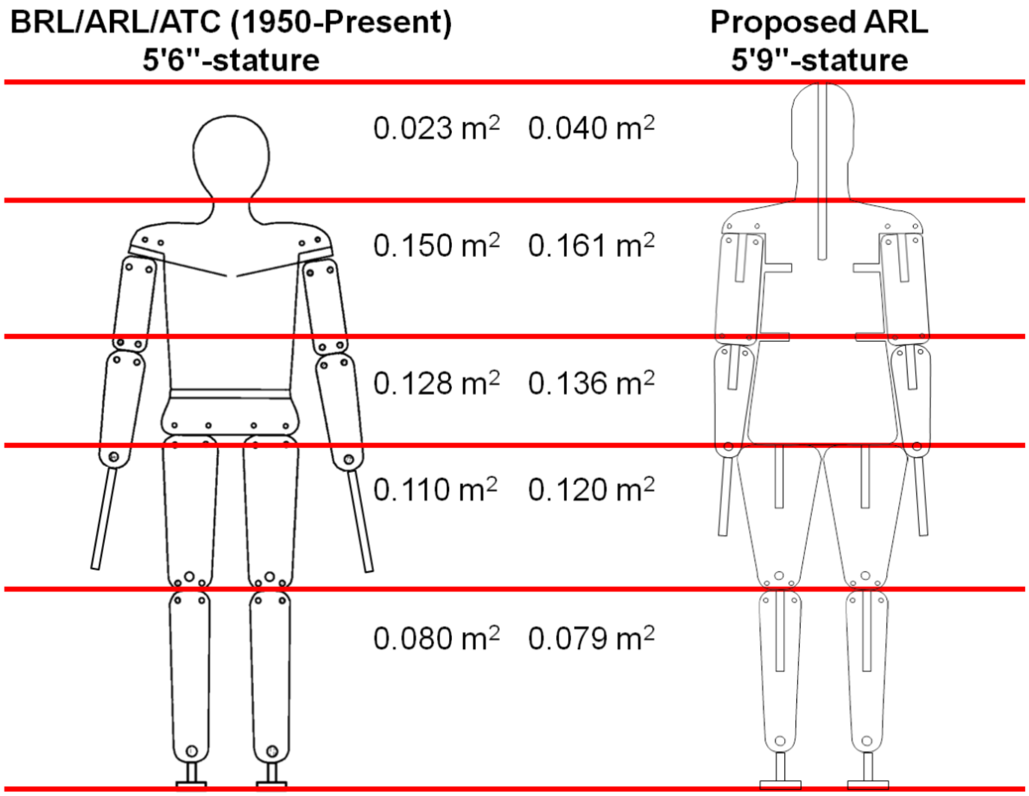

Fig. 7 A comparison of the frontal presented areas of the standing BRL and proposed ARL plywood ballistic mannequins, based on zones above the ground plane

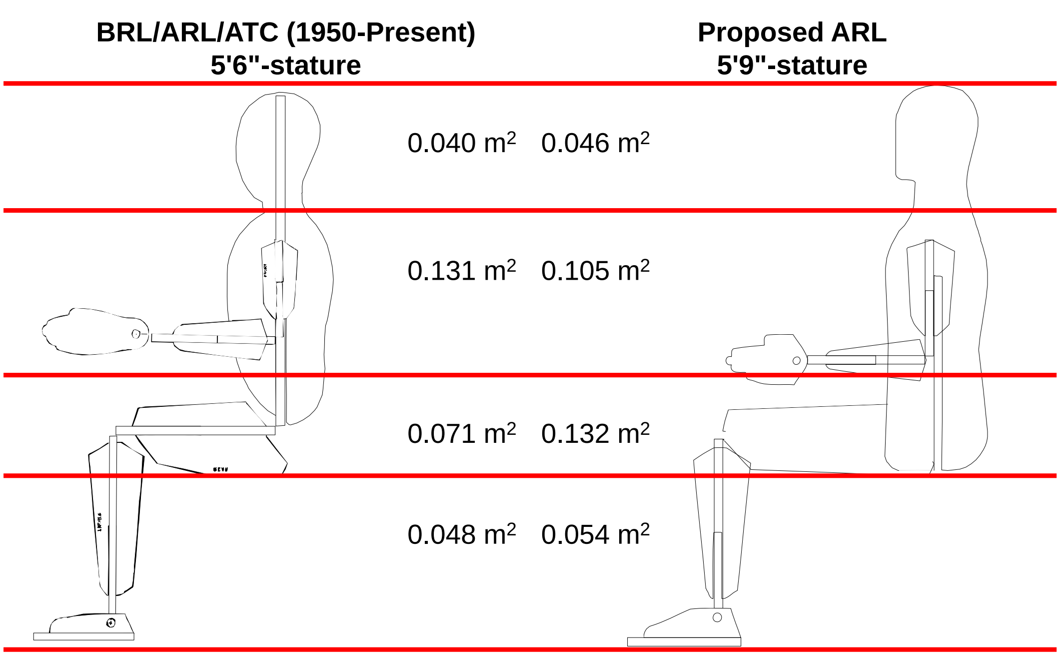

Fig. 8 A comparison of the sagittal presented areas of the seated BRL and proposed ARL plywood ballistic mannequins, based on zones from the seat pan

Several simple Bayesian probability statistics (BPS) can be used to assess the quality of the target to accurately predict a “hit” or a “miss”; the quality of a test or target can be described by the metrics of sensitivity, specificity, and accuracy; these metrics are independent of the prevalence. Sensitivity is the probability of the plywood ballistic mannequin registering a “hit” given a real “hit” on an unspecified Soldier; from the perspective of lethality/vulnerability analyses, the metric sensitivity reflects the probability of the model registering a hit given a validated hit. Specificity is the probability of the plywood ballistic mannequin registering a “miss” given a validated miss.

The value of a test (or target) cannot be inferred from the quality, since value is also a function of prevalence and the purpose (or application) of the test (or target). Accuracy is often misapplied to infer value; it cannot. Although the analyst might often infer that a more accurate test (or target or model) is better than a less accurate one, that test might still be inadequate to provide any value.[52] BPS metrics, positive likelihood ratio (+LR), and negative likelihood ratio (–LR) are often used to assist an analyst to infer value, since these metrics are specific to the purpose of the test (or target) (i.e., Is the target better suited to assess hits or to assess misses?).

Given the diversity of the human population, the sensitivity, specificity, and accuracy of a single target description are a function of the granularity; the quality and value of a single target description, which is used to represent that population, rapidly declines with increasingly finer granularity.[53,54] When granularity is restricted to body parts, ensuring reliability is greater than 50%, the sensitivities and accuracies of the proposed ARL mannequin’s component parts are superior to those of the BRL mannequin, respectively (Table 4).

Since the proposed ARL ballistic mannequin is a single representative, like the BRL ballistic mannequin, it too will impart a lethality bias by understating ballistic susceptibility, but given its larger presented area and more representative location of that area(s), this bias is not as severe. This bias would be more pronounced if the mannequins are articulated (i.e., kneeing, seated, or driving) or integrated with a platform (i.e., employed as a dismounted personnel target to assess vulnerability to fragments, generated by antipersonnel munitions, versus a crew personnel target within a vehicle to assess vulnerability to fragments, generated by a rocket-propelled grenade).

Table 4 A comparison of the Bayesian statistics of the standing BRL and the standing proposed ARL plywood ballistic mannequins

Summary Statistic [a]	Foot	Calf	Thigh	Pelvis	Chest	Head	Hand	Forearm	Upper Arm
BRL Plywood Ballistic Mannequin									
Sensitivity	0.45	0.60	0.67	0.50	0.71	0.56	0.72	0.64	0.67
Specificity	0.84	0.63	0.73	0.96	0.95	0.80	0.86	0.88	0.94
Accuracy	0.65	0.61	0.70	0.82	0.84	0.75	0.84	0.83	0.87
+LR	2.8	1.6	2.5	12.5	14.2	2.8	5.1	5.3	11.2
–LR	0.7	0.6	0.5	0.5	0.3	0.6	0.3	0.4	0.4
Proposed ARL Plywood Ballistic Mannequin									
Sensitivity	0.90	0.92	0.88	0.81	0.89	0.68	0.67	0.75	0.80
Specificity	0.93	0.91	0.91	0.91	0.91	0.91	0.93	0.92	0.91
Accuracy	0.91	0.91	0.90	0.88	0.90	0.86	0.88	0.88	0.88
+LR	12.9	10.2	9.8	9.0	9.9	7.6	9.6	9.4	8.9
–LR	0.1	0.1	0.1	0.2	0.1	0.4	0.4	0.3	0.2

[a]These Bayesian statistical metrics are calculated specific to the frontal perspective.

3.3 Avoiding the Anecdotal Fallacy

When the representative heuristic is employed, the anecdotal fallacy is avoided when the Kaufman uncertainty principle for geometric modeling is satisfied[54]:

$$P = 0.5 \leq erf\left[\frac{x}{\sqrt{2}\sigma_x}\right] \cdot erf\left[\frac{y}{\sqrt{2}\sigma_y}\right], \tag{3}$$

where

erf is the Gauss error function;

P is the reliability of the model or target;

x is one-half the width of the presented area (centimeters);

y is one-half the length of the presented area (centimeters);

σ_x is the component linear uncertainty probability (CLUP) / 0.674489750196…, where the CLUP is measured in the same direction and plane of the target's width or length (centimeters). The uncertainty is assumed to be a normal (i.e., Gaussian) distribution; and

σ_y is CLUP / 0.674489750196…, where the CLUP is measured in the same direction and plane of the target's length (centimeters). The uncertainty is assumed to be a normal (i.e., Gaussian) distribution.

This is the technical limit of the representative heuristic to avoid the anecdotal fallacy, since it ensures the geometric model has at least 50% reliability (i.e., the target description is representative of 50% or more of the population). It also ensures the most accurate *single* description.[55] If more detail is required, then the modeler or analyst must consider the anecdotal nature in its subsequent results or employ a probabilistic or stochastic approach, including tolerances or multiple target descriptions. Equation 3 is also a definition for average presented area.

Whereby the geometric model is being employed to assess ballistic threats, the constraint for general ballistic vulnerability analyses becomes less restrictive and provides the most accurate single target description[28]:

$$P = 0.5 \le erf\left[\frac{x + t_x}{\sqrt{2}\sigma_x}\right] \cdot erf\left[\frac{y + t_y}{\sqrt{2}\sigma_y}\right], \tag{4}$$

where

t_x is one-half the width of the threat's presented area (cm); and

t_y is one-half the length of the threat's presented area (cm).

However, the modeler or analyst who employs the representative heuristic will often pursue finer granularity and more details; the result is a lethality bias[56] in subsequent BVL analyses.

Yet, if the analyst is employing the familiar BVL model, i.e., $1 = [P_{hit}] + [P_{miss}]$, where $[P_{hit}]$ is the probability of a hit and $[P_{miss}]$ is the probability of a miss, this binary model is bound by a constraint that conflicts with that desire for finer granularity[28]:

$$P = 1 \approx erf\left[\frac{x + t_x}{\sqrt{2}\sigma_x}\right] \cdot erf\left[\frac{y + t_y}{\sqrt{2}\sigma_y}\right]. \tag{5}$$

This constraint results in a survivability bias[57] within subsequent BVL analyses.

A more sophisticated BVL methodology includes the "false hits" and "false misses" by employing BPS:

$$1 = \left[P_{true\ hit}\right] + \left[P_{false\ miss}\right] + \left[P_{true\ miss}\right] + \left[P_{false\ hit}\right]$$

$$1 = \left[P_{modeled\ hit}\right]\left[PPV\right] + \left[P_{modeled\ miss}\right]\left[1 - NPV\right] + \left[P_{modeled\ miss}\right]\left[NPV\right] + \left[P_{modeled\ hit}\right]\left[1 - PPV\right]$$

where

NPV is the BPS metric negative predictive value; and

PPV is the BPS metric positive predictive value.

This approach readily accommodates the potential differences between the representative heuristic and the population with its uncertainty and variability, and allows more modeled details to be retained.

Irrespective of these 2 approaches, both constraints (i.e., Eqs. 4 and 5) define the relationship amongst a geometric model's granularity, its reliability, the uncertainty of the component's position(s), and the size of the ballistic threat. Granularity cannot be finer without losing reliability and sacrificing accuracy and value, unless the subsequent analyses are restricted to relatively large ballistic threats.

3.4 Employing the Plywood Mannequin Correctly

If the standing plywood ballistic mannequin is properly employed, a fragment's hit registered on a plywood component should only be assessed as an assault on that component. The granularity should not be reduced below the major body part of a foot, calf, thigh, pelvis, torso and chest, head, upper arm, forearm, and hand.

The head component should not be divided into smaller components, such as forehead, eyes, jaw, etc. The upper portion of the plywood component of the mannequin's head should not be defined as the mannequin's forehead; the lower portion of the plywood component of the mannequin's head should not be defined as the mannequin's chin or jaw.[58] As such, it is inappropriate to use the ORCA model in subsequent damage analyses.

Such actions would violate the aforementioned constraints (i.e., Eqs. 3 and 4) and ensure the resultant analyses are anecdotal.

Given the first constraint (Eq. 3) (i.e., a reliability greater than 50%) and the US Army male population with a σ_y = 6.68 cm[59] (i.e., CLUP = 4.5 cm), the smallest portion on the plywood component of the standing mannequin's head must measure at least 9 cm in vertical height. Eyes, ears, chins, noses, etc., are features too small to reliably include in BVL analyses that employs only a single target description for such a diverse population. If such small features are included, the reliability of the plywood ballistic mannequin is quickly reduced to 15% or much less.

By comparison, the segments of the head of the ComputerMan target description within the ORCA software suite only measure 1.4 cm in height; such small features reduce the reliability of the ballistic ComputerMan to 0%. This description and its product are anecdotal unless the σ_y of those segments can be reduced to 1.04 cm or less (i.e., CLUP $\leq$ 0.70 cm), such as by restricting ORCA's application to personnel body armor. Of course, the alternative is to restrict ORCA's appliance to only assess the effects of insulting threats of 7.6-cm diameter or larger.

Given the third constraint (Eq. 5) and the US Army male population, the smallest portion of the plywood component of the mannequin's head must exceed 54 cm in vertical height, meaning only very general statements should be made, since such a large component could represent the presented areas of the head, neck, shoulders, chest, or lower torso.

The proposed ARL plywood ballistic mannequin is designed to accommodate the constraint of Eq. 3 and provides greater accuracy (i.e., better prediction of both true hits and true misses) and superior value than the BRL plywood ballistic mannequin.

4. Conclusions

The plywood ballistic mannequins are a blunt tool because of the low reliability in the definition of possible personnel. Employed correctly, the mannequins can provide only general information.

There is an enduring institutional mindset to preserve the representative heuristic and overanalyze data, regardless of the technical uncertainty, generating an interesting anecdotal narrative, which has less statistical value.

4.1 Marine-Grade Plywood

Even with 90% confidence intervals, the V_{50}'s value has poor reliability (i.e., poor repeatability and poor consistency). Based on this limited testing, there is a significant difference amongst plywood. This difference is significant even between sheets of the same wood species, ply, and manufacturer. This uncertainty of the plywood sheets' V_{50} may limit the granularity of subsequent fragment-plywood penetration and perforation analysis.

The current callout on the materials of construction (i.e., "¾" plywood, marine grade or equal"[5]) is inadequate.

The impact of the variability of V_{50} on PVA was not a part of this study.

4.2 Ballistic Mannequin

The uncertainty of the human population, posture, and positioning limits the value of a single target description; reliability is sacrificed for the simplicity of the narrative.

Given the diversity of the human population, body-part-level analyses are more accurate for predicting hits and misses.

As a representative of the US Army male population, the proposed ARL plywood ballistic mannequin is statistically superior to the BRL plywood ballistic mannequin.

5. Recommendations

ARL SLAD recommends the following actions:

- Additional testing of plywood properties is needed to provide a more consistent test item. Possible future callouts for materials of construction might be, “Weight of each 4- by 8-ft sheet of plywood must be greater than 68.5 lb, minimum”, or “0.75-inch plywood, marine-grade or equal, 10.5 kg/m^2 minimum areal density”.
- Whether the observed uncertainty in V_{50} can appreciably affect the PVA was not a part of this study. Subsequent limited analysis, employing ORCA, version 4.16, estimated an uncertainty in weighted task average impairment values[60] of $\pm$0.05 standard deviation minimum if the uncertainty in V_{50} was only $\pm$40 m/s. More rigorous sensitivity analysis is required to determine the effect and magnitude of this lack of reliability on PVA.
- For the representation of US Army personnel, the revised plywood ballistic mannequin should be employed in future LFT.
- The use of ORCA can readily reduce the value of LFT. The Kokinakis-Sperrazza-type equations should be regenerated, based on ORCA, to provide a better predictor of damage(s) and residual capabilities given a fragment’s penetration to a body part.

6. Preparing Activity

This document was prepared by ARL, SLAD, Aberdeen Proving Ground, MD, 21005-5068. Points of contact for this action are Matthew Kaufman, telephone (410) 278-3063 or DSN: 298-3063, e-mail Matthew.B.Kaufman.CIV@mail.mil; and Linda L Moss, telephone (410) 278-6513 or DSN: 298-6513, e-mail Linda.L.Moss6.CIV@mail.mil.

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48. The estimated weight of the mannequins is based on a plywood areal density of 10.5 kg/m^2.

49. The hands of the BRL mannequin have been rotated 90°. Cross-members have been removed for clarity.

50. Kaufman M. Ballistics targets for assessing survivability/vulnerability of us army men and women. Registration number: VAU000962290. Bel Air, MD; 2007 Nov. 26 [accessed 2014 Dec 8]. http://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?DB=local&PAGE=First.

51. Kaufman, M. Board (7-ply) American Army male ballistic mannequin, BAAMBaM. Registration number: VAU990-611. Bel Air, MD; 2009 Mar 26. [accessed 2014 Dec 3]. http://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?DB=local&PAGE=First.

52. There is also the situation termed the "Accuracy Paradox", whereby a predictive model with a given level of accuracy may have greater value than another model with the same or greater level of accuracy, depending upon whether the application of the model is to predict hits (i.e., positives) or to predict misses (i.e., negatives).

53. The erroneous belief that a more detailed model has provided greater value is the "Modeler's Paradox". Greater detail enhances confidence at the expense of reliability. Therefore, the results from a model may be anecdotal, reducing the value rather than enhancing value of the results to support recommendations.

54. Kaufman M. Kaufman uncertainty principle for geometric modeling. Registration number: TXU1-364-300. Bel Air, MD. 2007 July 2. [accessed 2014 Dec 8]. http://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?DB=local&PAGE=First.

55. The sum of the probabilities of false hits and false misses is a minimum.

56. The representative heuristic results in susceptibility being understated; therefore, lethality will be understated, and overkilled is encouraged. Therefore, the bias in the methodology

that supports ballistics vulnerability/lethality analyses will be in opposition to the methodology that supports ballistics vulnerability/survivability analyses.

57. In this case, the representative is a large, all-encompassing volume, which is larger than any one representative; therefore, susceptibility is overstated.

58. The 50th percentile presented area of the males' heads is not the same as the presented area of the head of a 50th percentile male. The former is a composite of a population; the latter reflects an individual and is anecdotal. Analyses, based on the latter, will overstate the probability of an outcome; the result is the anecdotal fallacy, "The analyst will overstate what he thinks he knows and understate what he doesn't know."

59. Human Systems Integration Information Analysis Center (HSIIAC). 1988 US Army Male Anthropometry Survey, 1774 Data Sets [accessed 1998 Aug 8]. http://www.hsiiac.org.

60. These values are based on the job of the assaulting infantry rifleman (ORCA Ver. 2.1).

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Appendix A. When Determinism Is Inappropriate

The representative (or representativeness) heuristic is truly a judgmental or decision-making shortcut, marked by the declaration that the input variables and constraints are "representative" often with only personal experience to infer whether the values are valid or inconsequential in the magnitude of the anticipated outcome. The representative heuristic is more indicative of an understanding in the standardized or accepted mathematical methodology rather than an understanding in the science or physics of the problem. It is only via that personal familiarity that this shortcut has been employed and reinforced—until it catastrophically fails, and a bigger safety factor or design margin is added to preclude a similar failure in the future.

Lacking a good understanding of probabilities, possibilities, reliability, and confidence—and lacking sufficient grounding in mathematics and science—most people, especially analysts, will try to infer answers where they lack the understanding or adequate information to make an informed decision.

Although this heuristic is badly chosen for decision making, it is certainly inappropriate for problem solving.

When input variables and constraints are singular values, a deterministic approach can be employed by engineers, scientists, and analysts. However, when these same variables and constraints are not monolithic but are uncertain (e.g., values with tolerances or a population of values defined by a mean and a standard deviation), the deterministic methodology can readily yield an anecdotal or wrong answer. Figure A-1 is a pictorial presentation of the analytical process that engineers, scientists, and analysts are supposed to be employing.

Regardless of the approach, the analyst should ensure the values are both reasonable and valid. If the values are not, there should be no expectation that the results are valid. Similarly, if the data set of inputs and constraints is not valid, then the engineer or analyst must accept the consequences—a potentially wrong answer.

Are the valid values monolithic or is there distribution of values? Uncertainty in input variables will result in uncertainty in the results from the methodology. Therefore, if the spatial density of the data set of input variables and constraints does not exceed 50% reliability, then the resultant may also be only anecdotal (i.e., have a reliability less than 50%). Therefore, if a more accurate view of the results is desired, the deterministic approach must be abandoned and probabilism must be considered (i.e., such metrics as tolerances, standard deviation, probable error, sensitivity, and specificity have to be included) in the analytical process.

In some cases, this may mean that the deterministic process is employed multiple times—a stochastic approach whereby a variety of input variables and constraints are used to determine the sensitivity and diversity of the outcome(s) to conditions.

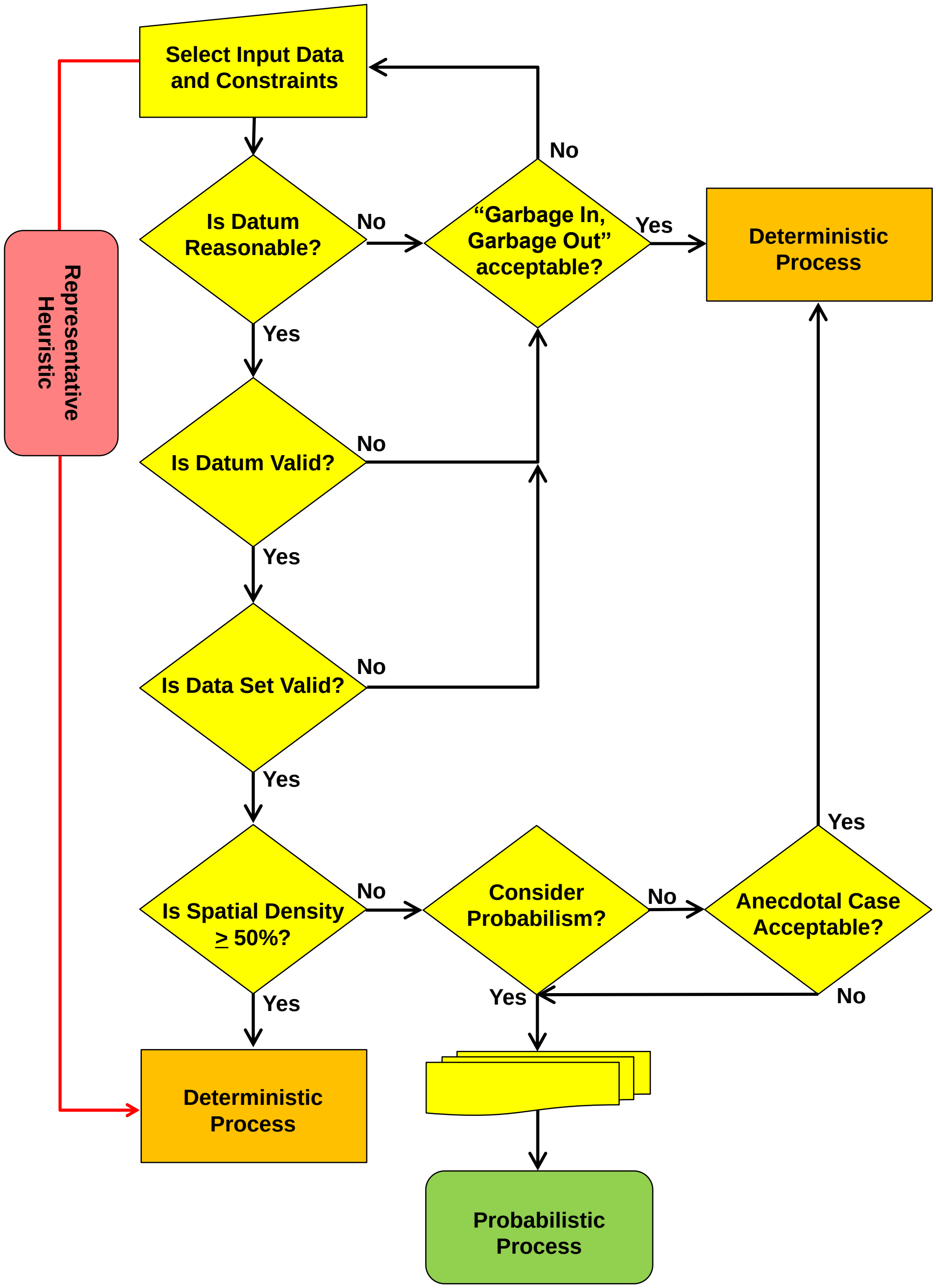

Fig. A-1 The flow process to determine whether a deterministic or probabilistic approach is necessary

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Appendix B. The American Plywood Association (APA) Wood Species Grouping

For the purposes of the American Plywood Association (APA), wood species are any softwood, hardwood, or trade group listed in Table B-1 or that satisfy Product Standard 1-09[1]:

> The species of wood used to manufacture the plywood are classified into five groups based on their bending strength and stiffness: group 1 being the strongest and group 5 the weakest. The species are grouped on the basis of their mechanical properties for bending stiffness and bending strength as these are the most important properties for many plywood uses.
>
> The average and standard deviation data of the five important mechanical properties of clear, straight-grained solid wood of all species in each group were obtained in the green and dry condition. The five properties are bending modulus of elasticity (MOE), bending modulus of rupture, compression parallel to the grain, shear parallel to the grain, and compression perpendicular to the grain. For each of the five properties, the limiting property value that has been assigned to any group that includes that wood species was determined at the dry (12% for MOE, 15% for all other properties) and green moisture content. The maximum assignable MOE value is either the wood species average increased by 10% if volume data is available in American Society for Testing and Materials (ASTM) Standard D2555[2] or the wood species average if no volume data exists or if it is a foreign species.
>
> The strength properties are calculated in one of the following three methods:
>
> (i) Method A species in ASTM D2555:
>
> $$Maximum\ Assignable = \left(\frac{species\ average}{variability\ index}\right) - 1.18 \times (species\ standard\ deviation)$$
>
> (ii) Method B species in ASTM D2555:
>
> $$Maximum\ Assignable = (species\ average) - 1.48 \times (species\ standard\ deviation)$$
>
> (iii) Domestic species with no volume data and foreign species:
>
> $$Maximum\ Assignable = (species\ average) - 1.645 \times (species\ standard\ deviation)$$
>
> The maximum assignable property must meet or exceed all property values listed in Table C1 [Table B-1 here] for the species group in order to be assigned that group.

[1] Voluntary Product Standard. PS 1-09, structural plywood. Tacoma (WA): APA, The engineered wood association headquarters; 2010 June. [accessed 12 June 2014]. www.apawood.org.

[2] ASTM D2555-06. Wood standard. Standard practice for establishing clear wood strength values. Conshohocken (PA): American Society for Testing and Materials, International; 2011.

Table B-1 The classification of North American wood species and minimum acceptable properties.[a]

Group 1	Group 2		Group 3	Group 4	Group 5
North American Species					
American beech	Cedar	Pine	Red alder	Aspen	Basswood
Birch	Port	- Pond	Paper birch	- Bigtooth	Poplar
- Sweet	Orford	- Red	Alaska cedar	- Quaking	- Balsam
- Yellow	Cypress	-Virginia	Subalpine fir	Cedar	
Douglas fir[b]	Douglas fir[b]	Western	Eastern hemlock	- Incense	
Western larch	- Balsam	White	Bigleaf maple	- Western red	
Sugar maple	- Calif. red	Spruce	Pine	Cottonwood	
Southern pine	- Grand	–Black	- Jack	- Eastern	
- Loblolly	- Noble	–Red	- Lodgepole	- Black (western poplar)	
- Longleaf	- Pacific	–Sitka	- Ponderosa		
- Shortleaf	- Silver	Sweetgum	- Spruce	Pine	
- Slash	- White	Tamarack	Redwood	- Eastern White	
Tanoak	Western	Yellow	Spruce	- Sugar	
	Hemlock	Poplar	- Engelmann		
	Black maple		- White		
Non-North American Species					
Apitong[c,d]	Lauan				
Kapur[c]	- Almon				
Keruing[c,d]	- Bagtikan				
Pine	- Mayapis				
- Caribbean	- Red Lauan				
- Ocote	- Tangile				
	-White Lauan				

Group 1		Group 2		Group 3		Group 4		Group 5	
Modulus of Elasticity (million psi)									
Green	**Dry**	**Green**	**Dry**	**Green**	**Dry**	**Green**	**Dry**	**Green**	**Dry**
1.483	1.857	1.249	1.588	1.047	1.310	0.924	1.146	0.748	1.100
Bending Strength (psi)									
5300	8064	3662	6297	3681	5985	3483	5389	2843	4345
Compression Parallel to Wood Grain (psi)									
2425	4123	1833	3163	1548	2662	1570	2630	1190	2187
Shear Strength Parallel to Wood Grain (psi)									
665	855	532	692	524	652	476	633	387	542
Compression Perpendicular to Wood Grain (psi)									
193	354	124	221	123	212	97	152	73	132

Note: 1 psi = 6,895 Pa.

[a]Table is based on Tables 1, A1, and C1 from the following source: Voluntary Product Standard. PS 1-09, structural plywood. Tacoma (WA): APA, The engineered wood association headquarters; 2010 June. [accessed 12 June 2014]. www.apawood.org. Species classified in accordance with ASTM D2555 (Standard Practice for Establishing Clear Wood Strength Values, 2011).

[b]Douglas fir from trees grown in the states of Washington, Oregon, California, Idaho, Montana, Wyoming, and the Canadian provinces of Alberta and British Columbia shall be classed as Group 1. Douglas fir from trees grown in the states of Nevada, Utah, Colorado, Arizona, and New Mexico shall be classed as Group 2.

[c]Each of these names represents a trade group of woods consisting of a number of closely related species.

[d]Species from the genus *Dipterocarpus* marketed collectively: Apitong if originating in the Philippines; Keruing if originating in Malaysia or Indonesia.

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Appendix C. US Army Ballistic Research Laboratory (BRL) Plywood Ballistic Mannequin

The drawings for 28 wooden components for the ballistic mannequin, which had been employed in live-fire testing in support of the Armored Systems Modernization program of the 1980s, illustrate a simple 3-dimensional plywood target description for personnel (Fig. C-1). Its smaller stature (i.e., 5 ft, 6 inches), relative to US military personnel, enabled it to be more easily installed into interior crew spaces. However, its shorter seated height, shorter stature, and smaller frontal presented area,[1] relative to US military personnel, impart a lethality-bias by understating ballistic susceptibility.

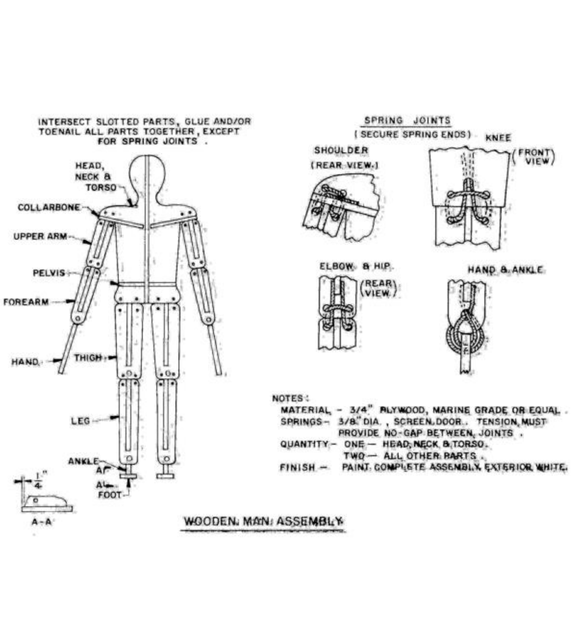
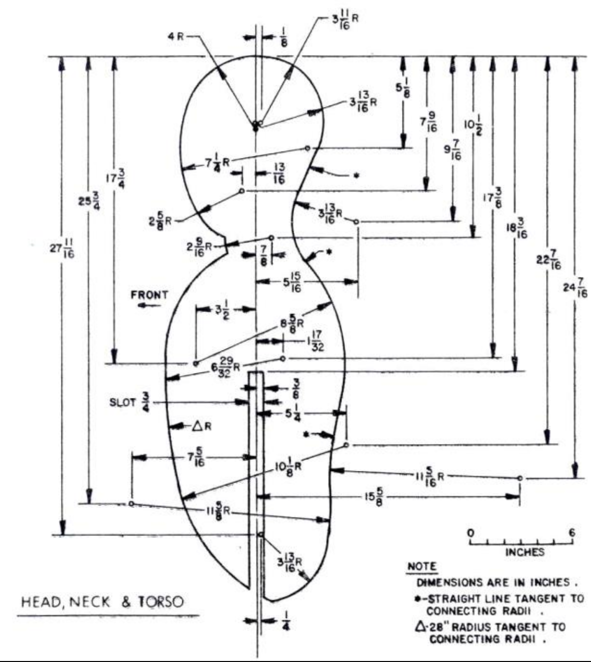
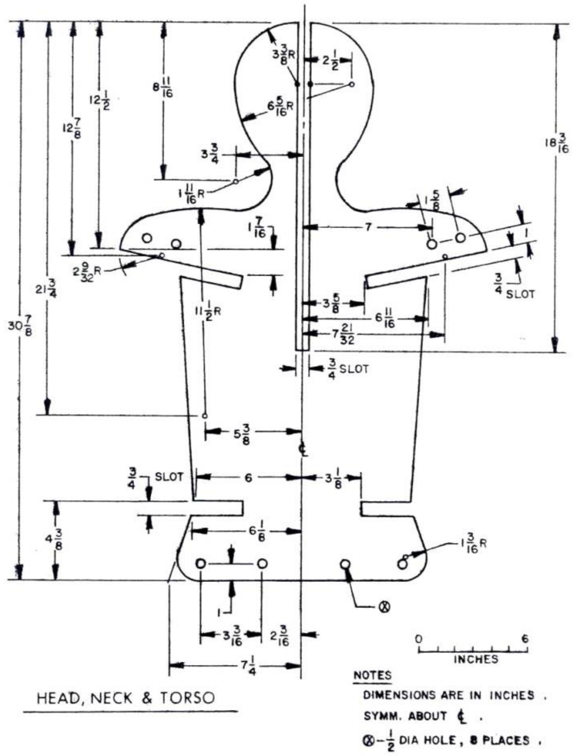
<table>
<tr><th>Assembly</th><th>Head, Neck and Torso (Profile), 1 each</th></tr>
<tr><td>
</td>
<td>
</td></tr>
</table>

Fig. C-1 Drawings for the US Army Ballistic Research Laboratory plywood ballistic mannequin[2]

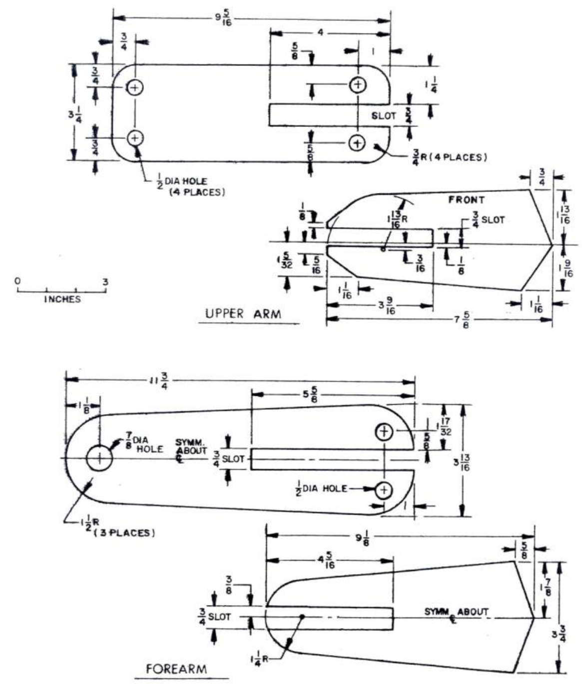
[1] Personal communication with W Mermagen and P Gillich. US Army Research Laboratory, Aberdeen Proving Ground, MD; 6 April 2007. Subject: FYI, Plywood Mannequin/COMPUTERMAN vs. US Army Male.

[2] Email communication with R Prather. US Army Research Laboratory, Aberdeen Proving Ground, MD; 16 April 2004.

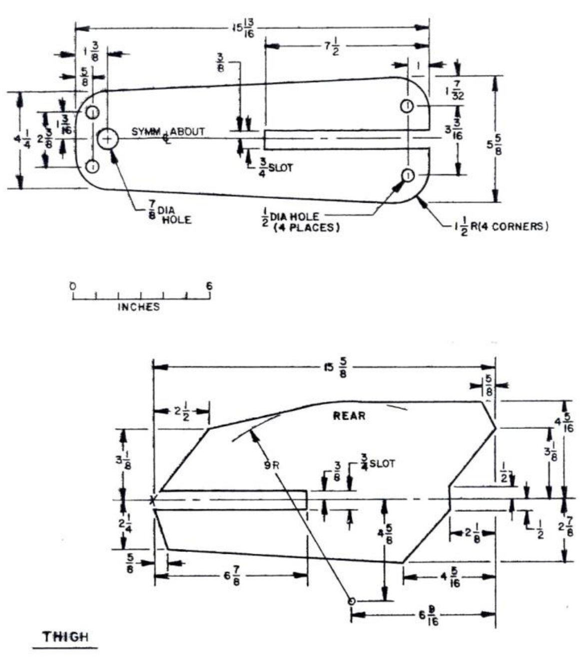
Head, Neck and Torso (Frontal), 1 each



Upper and Lower Arm, 2 each



Thigh, 2 each



Lower Leg, Ankle and Foot, 2 each

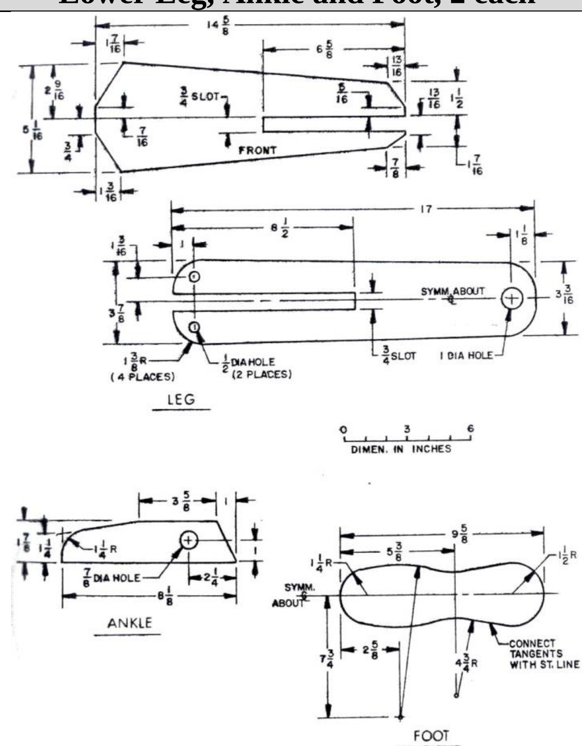
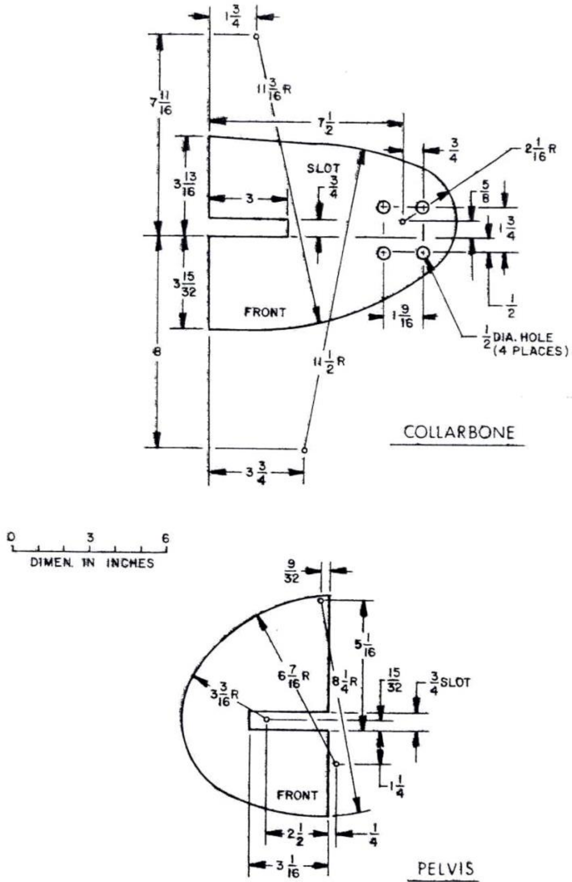


Fig. C-1 Drawings for the US Army Ballistic Research Laboratory plywood ballistic mannequin (continued)

Collarbone and Pelvis, 2 each	Hand, 2 each



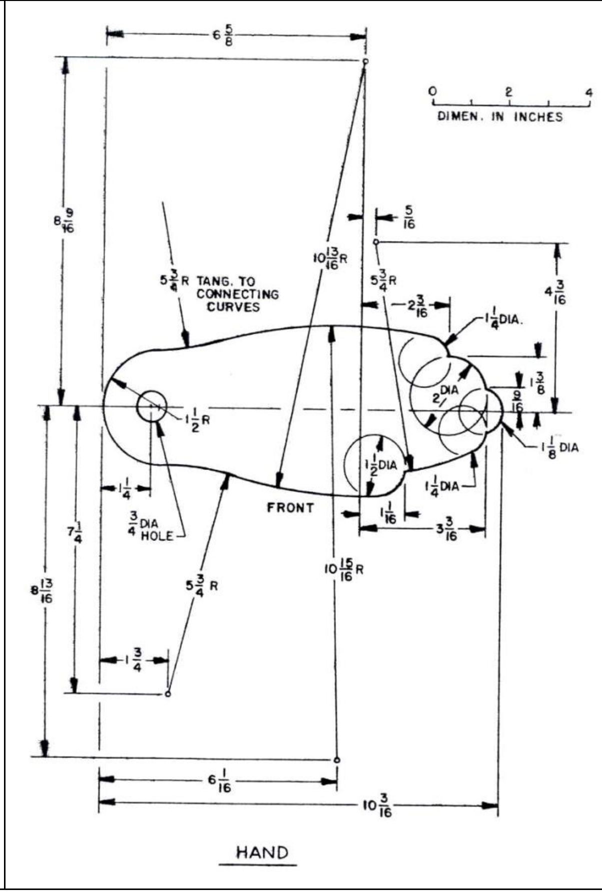


Fig. C-1 Drawings for the US Army Ballistic Research Laboratory plywood ballistic mannequin (continued)

Appendix D. A Modified Langlie Sequential Firing Procedure[1]

[1] Excerpted from Collins JC, Moss LLC. LangMod user's manual. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2011 June. Report No.: ARL-TN-437.

The sequential firing procedure based on the Langlie method (DARCOM Pamphlet 706-103, 1983 and TOP 2-2-710) was conducted to select velocities for obtaining estimates of the V_{50} ballistic limit. Several modifications were made to obtain velocities away from the mean to better estimate the entire response curve, and to establish stopping rules.

1. Select lower and upper projectile velocity limits (gates) for the threat tested. The lower gate is that velocity where we would expect to consistently see partial penetration. The upper gate is that velocity where we expect to consistently see complete penetration. These gates should be set so that lower gate is at least 20 m/s lower than the lower limit of the expected zone of mixed results and the upper gate is at least 20 m/s higher than the upper limit of the expected zone of mixed results.

2. Fire the first round at a velocity midway between these two limits.

3. If the first round results in a complete penetration, drop the velocity of the second round halfway between the first round velocity and the lower limit velocity; if the first round results in a partial penetration, raise the velocity of the second round to halfway between the first round velocity and the upper limit velocity.

4. If the first two rounds result in a reversal (one partial, one complete), fire the third round midway in velocity between the velocity of the first two rounds. If the first two rounds result in two partials, fire the third round at a velocity half way between the second round and the upper limit. If the first two rounds result in two complete penetrations, fire the third round at a velocity half way between the velocity of the second round and the lower limit.

5. If a reversal does not occur in three rounds adjust the lower and upper limits as follows. If all rounds resulted in partials, raise the lower and upper limits by 20 m/s and fire the next round halfway between the last round and the new upper limit. If all rounds resulted in complete penetrations, decrease the lower and upper limits by 20 m/s. Fire the next round half way between the last round and fire the next round halfway between the last round and the new lower limit.

6. Fire the succeeding rounds as follows:

   a. If the preceding PAIR of rounds resulted in a reversal, fire at a velocity midway between the two velocities.

   b. If the last two rounds did not produce a reversal look at the last four rounds. If the number of completes and partials is equal, fire the next round between the velocity of the first and last round of the group. If the last four did not produce equal numbers of partials and completes, look at the last six, eight, . . . , until the number of partials and completes is equal. Always fire at a velocity that is half way between the first and the last round of the group examined (not necessarily the highest and lowest of the group).

c. If the conditions in 6b above cannot be satisfied and the last round resulted in a complete, fire the next round at a velocity midway between the last round and the lower velocity limit, or if the last round resulted in a partial, fire at a velocity midway between the last round and the upper velocity limit.

d. Continue as in 6a and 6b above for a minimum of 8 shots and a maximum of 15 (for this firing program) until the following stopping rules can be applied:

   i. Obtain a zone of mixed results (at least one partial penetration has a higher velocity than a complete penetration). The size of the zone of mixed results is defined as the difference in velocity between the highest partial penetration and the lowest complete penetration.

   ii. The average of the complete penetrations is larger than the average of the partial penetrations.

   iii. The spread of the tightest (smallest velocity spread among all shots) three partial penetrations and the three complete penetrations is within 38 m/s (125 ft/s).

   iv. Ensure that the data set contains values approximately ± 1 Δ from the V_{50} that is estimated from the tightest three partial penetrations and three complete penetrations. Set Δ to ± 20 m/s unless a wider band is required as given in step 5. (This value does not have to be the same as the gate radius). If velocities do not exist at these outer values, test at a velocity of $\boldsymbol{V_{50}}$ + Δ m/s and/or $\boldsymbol{V_{50}}$ – Δ m/s. Where shots permit, (assuming the previous data were properly obtained with less than 10 shots) an additional shot(s) may be conducted at the following velocities to provide more balanced data:

   - between the lowest shot (the aforementioned $\boldsymbol{V_{50}}$ – Δ) and the lowest complete penetration
   - between $\boldsymbol{V_{50}}$ + Δ and the highest partial penetration.

Use all data to get estimates the $\boldsymbol{V_{50}}$ using maximum likelihood estimation or general linear models.

The following is an example using the strategy and the rules to ensure a good data set:

Shot Number	Strategy	Velocities		Result
	(a) Gates	560	640	
1.	(b) Midpoint	600	1	CP
2.	(c)	580	0	PP
3.	(d)	590	1	CP
4.	(f1)	585	1	CP
5.	(f3)	572	0	PP
6.	(f1)	578	0	PP

We now have 3 PP and 3 CP. Compute the delta (spread) = 600 – 572 = 28.

This is within 38 m/s, but we don't have a zone of mixed results. Continue testing.

7.	(f2 based on 4 shots) (averaged shots 3 and 6)	584	0	PP

Do we have a zone of mixed results? No. Continue testing.

8.	(f2 based on 6 shots) (averaged shots upper gate and 7)	612	1	CP

Do we have a zone of mixed results? No

9.	(f1)	598	1	CP

Do we have a zone of mixed results? No

10.	(f2 based on 4 shots) (averaged shots 6 and 9)	588	0	PP

Do we have a zone of mixed results? Yes

Is the average of the CP (597.0) greater than the average of the PP (580.4)? Yes

What is the average and spread of the 3 highest PP (580, 584, 588) and 3 lowest CP (585, 590, 598)? 587.5 m/s with a spread of 18 m/s

Do we have data at least 587.5 ± 20 m/s (567.7 and 607.5)? No/Yes.

Test at 567.

11.	(f4)	567		
			0	PP

Stop testing.

Use all of the data to compute the parameter estimates of the response function.

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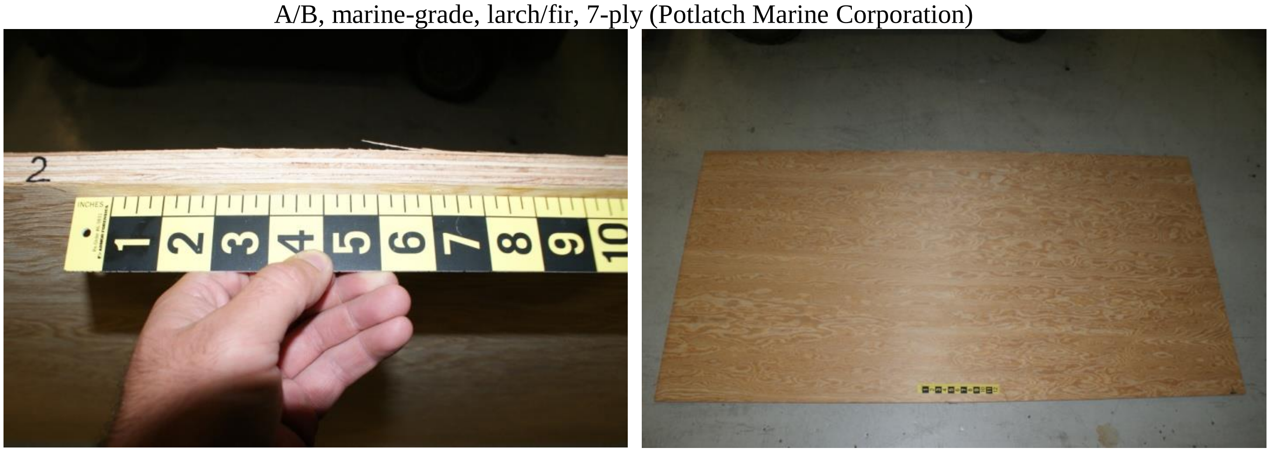
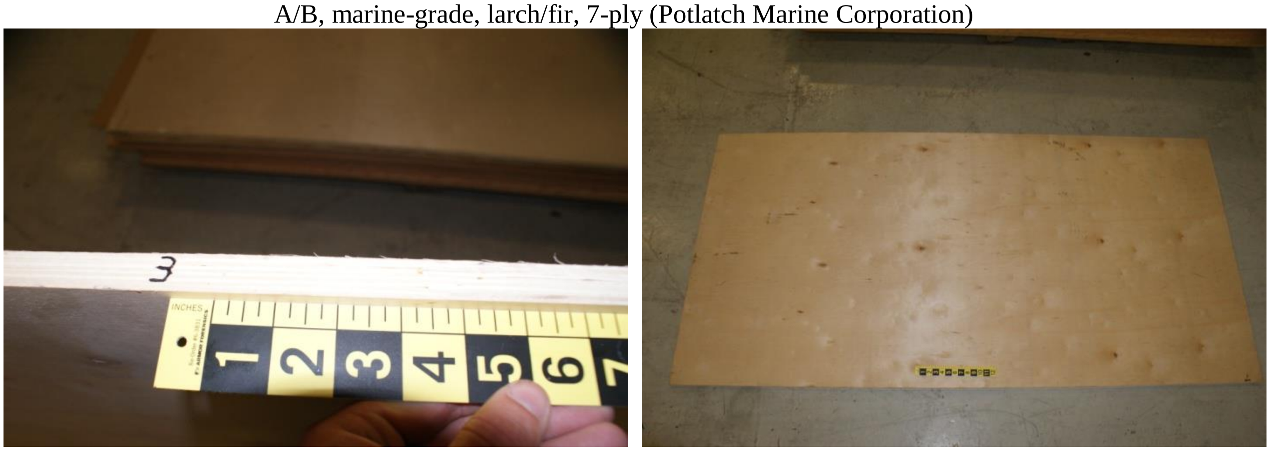
Appendix E. Photographs of the Plywood Specimens

A total of 12 sheets of plywood (i.e., 2 sheets from each group under this investigation) were purchased. Photographs were taken of the best face of each sheet and of the sheet's edge to document the number of ply (Fig. E-1). In order to estimate bulk density and areal density, the overall dimensions of each plywood sheet were measured, and each sheet was weighed prior to being cut into smaller samples. Testing to determine penetrating velocities only included plywood sample nos. 2, 4, 6, 8, 10, and 12.

A/B, marine-grade, larch/fir, 7-ply (Potlatch Marine Corporation)



A/B, marine-grade, larch/fir, 7-ply (Potlatch Marine Corporation)



B/B, birch hardwood, 11-ply, veneer core (Georgia-Pacific)

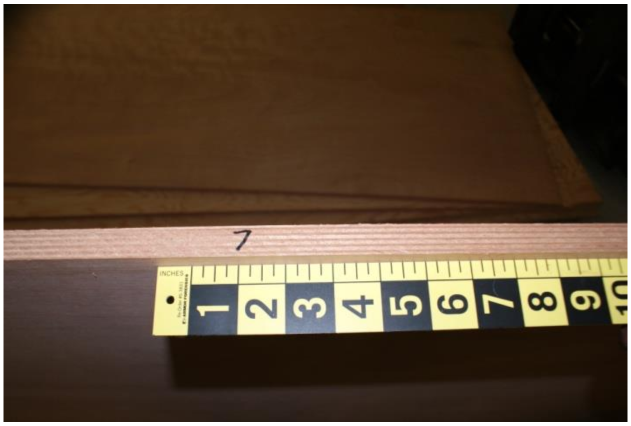
Fig. E-1 Photographs of the edges of the 12 plywood specimens (0.75-inch nominal thickness)

B/B, birch hardwood, 11-ply, veneer core (Georgia-Pacific)

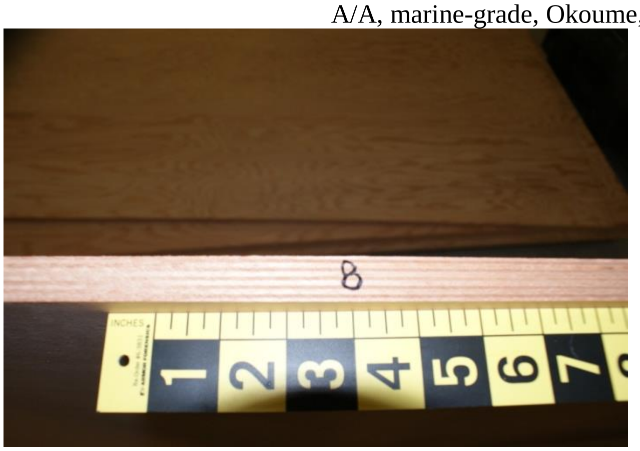
CDX, standard yellow pine, 5-ply (Georgia-Pacific)

CDX, standard yellow pine, 5-ply (Georgia-Pacific)

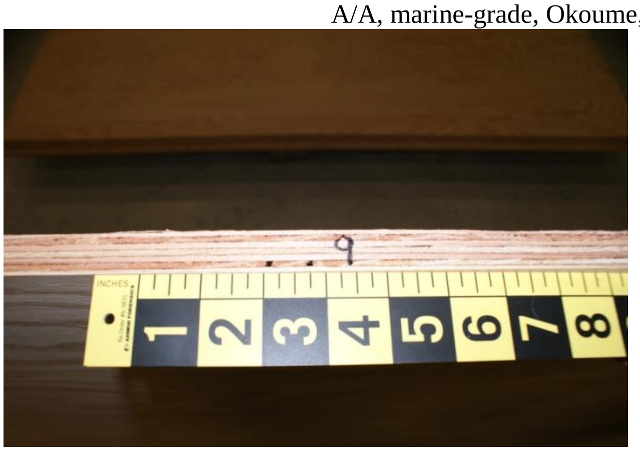
Fig E-1 Photographs of the edges of the 12 plywood specimens (0.75-inch nominal thickness) (continued)



A/A, marine-grade, Okoume, 11-ply (Allin Bruynzeel)



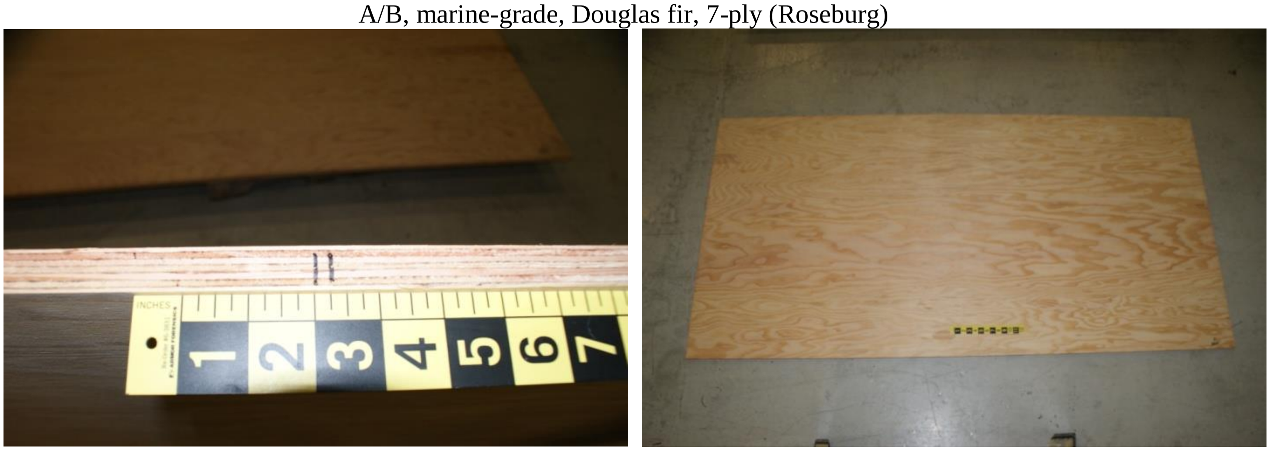
A/A, marine-grade, Okoume, 11-ply (Allin Bruynzeel)



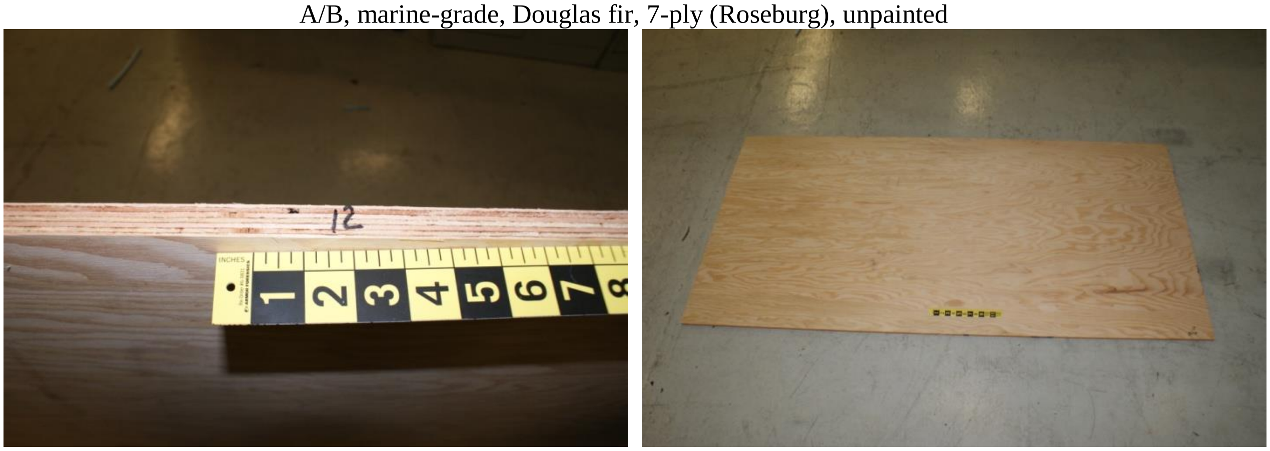
A/B, marine-grade, Douglas fir, 7-ply (Roseburg)

Fig E-1 Photographs of the edges of the 12 plywood specimens (0.75-inch nominal thickness) (continued)

A/B, marine-grade, Douglas fir, 7-ply (Roseburg)



A/B, marine-grade, Douglas fir, 7-ply (Roseburg), unpainted



A/B, marine-grade, Douglas fir, 7-ply (Roseburg), unpainted

Fig E-1 Photographs of the edges of the 12 plywood specimens (0.75-inch nominal thickness) (continued)

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Appendix F. V_{50} and Residual Velocity Test Summary

Velocities for determining V_{50} were selected by the modified Langlie sequential strategy as described in Appendix D[1]. The calculation of the V_{50} was determined using generalized linear models.[2,3] The data and response curves are shown in Figs. F-1 and F-2. Partial penetrations are plotted as 0 and complete penetrations as 1. The resulting fit of the data for each type of plywood is a response curve using the logistic distribution as an increasing function of velocity. Figure F-1 lists the mean (V_{50}) and standard deviation (σ_r or sigma_r) of the response curve for each plywood type. The 90% confidence interval is shown as the horizontal line at P[CP] = 0.5. Fig. F-2 combines the 6 curves.

Table F-1 provides the p-values for the pairwise comparisons of the response curves. Table F-2 provides the p-values for the pairwise comparison of just the V_{50} ballistic limit.

The residual velocities are pictorially present in Figs. F-3 through F-10.

[1] Collins JC, Moss LLC. LangMod user's manual. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2011 June. Report No.: ARL-TN-437.

[2] Collins JC. Quantal response: practical sensitivity testing. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2012 June. Report No.: ARL-TR-6022.

[3] Collins, JC. Quantal response: estimation and inference. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2014 Sep. Report No.: ARL-TR-7088.

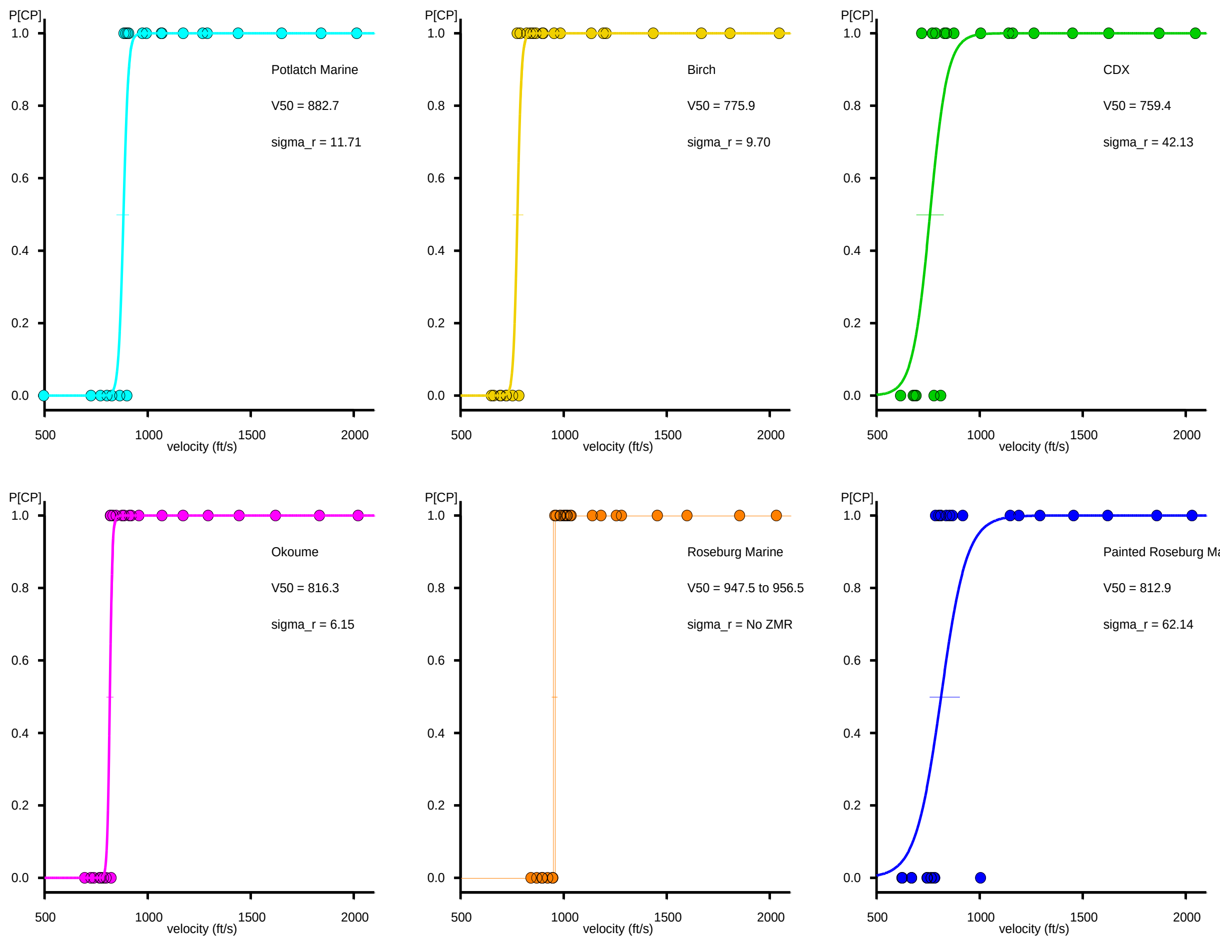

Fig. F-1 A comparison of the shots for V_{50} testing for the various plywood samples

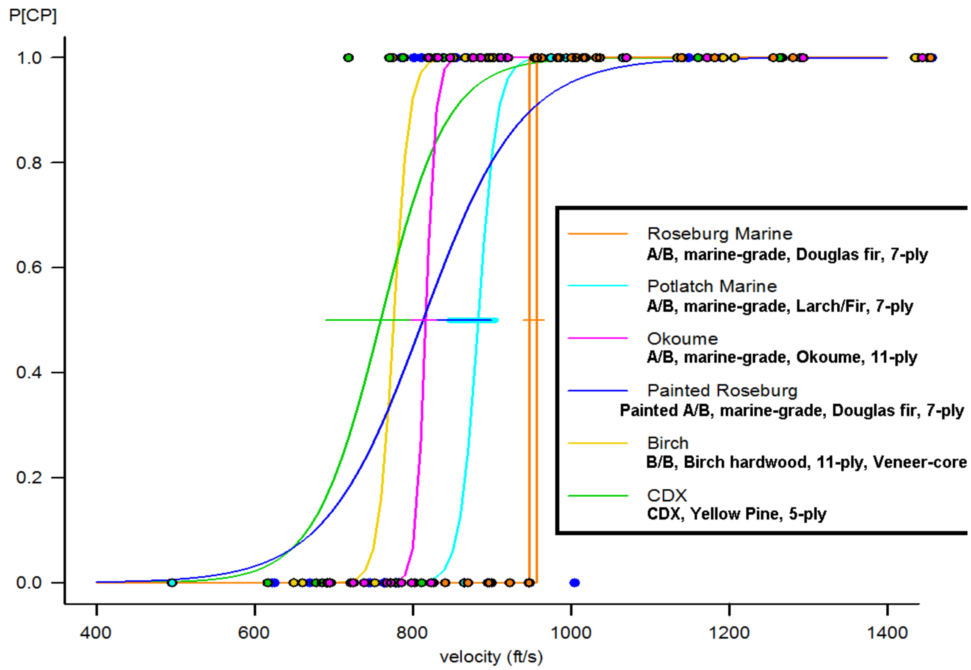

Fig. F-2 A comparison of the response curves (probability of penetration as a function of impact velocity) for the various plywood samples

Table F-1 P-values for the pair-wise comparisons of the response curves

	CDX, Yellow Pine, 5-ply. Manufacturer: Georgia-Pacific	B/B, Birch hardwood, 11-ply, veneer-core. Manufacturer: Georgia-Pacific, China	Painted A/B, marine-grade, Douglas fir, 7-ply. Manufacturer: Roseburg	A/B, marine-grade, Okoume, 11-ply. Manufacturer: Allin Bruynzeel	A/B, marine-grade, Larch/Fir, 7-ply. Manufacturer: Potlatch Marine Corporation	A/B, marine-grade, Douglas fir, 7-ply. Manufacturer: Roseburg
CDX, Yellow Pine, 5-ply. Manufacturer: Georgia-Pacific		0.2567	0.4809	0.0292	0.0185	< 0.0001
B/B, Birch hardwood, 11-ply, Veneer-core. Manufacturer: Georgia-Pacific, China			0.0718	0.0747	0.0035	< 0.0001
Painted A/B, marine-grade, Douglas fir, 7-ply. Manufacturer: Roseburg				0.0404	0.0847	< 0.0001
A/B, marine-grade, Okoume, 11-ply. Manufacturer: Allin Bruynzeel					0.0113	< 0.0001
A/B, marine-grade, Larch/Fir, 7-ply. Manufacturer: Potlatch Marine Corporation						0.0006
A/B, marine-grade, Douglas fir, 7-ply. Manufacturer: Roseburg						

Green	Not statistically significant
Orange	Significant at the 0.10 level
Yellow	Significant at the 0.05 level
Red	Significant at the 0.01 level

Table F-2 P-values for the pair-wise comparisons of the V_{50} ballistic limit

	CDX, Yellow Pine, 5-ply. Manufacturer: Georgia-Pacific	B/B, Birch hardwood, 11-ply, veneer-core. Manufacturer: Georgia-Pacific, China	Painted A/B, marine-grade, Douglas fir, 7-ply. Manufacturer: Roseburg	A/B, marine-grade, Okoume, 11-ply. Manufacturer: Allin Bruynzeel	A/B, marine-grade, Larch/Fir, 7-ply. Manufacturer: Potlatch Marine Corporation	A/B, marine-grade, Douglas fir, 7-ply. Manufacturer: Roseburg
CDX, Yellow Pine, 5-ply. Manufacturer: Georgia-Pacific		0.6228	0.2433	0.1239	0.0160	0.0033
B/B, Birch hardwood, 11-ply, veneer-core. Manufacturer: Georgia-Pacific, China			0.2867	0.0290	0.0046	<0.0001
Painted A/B, marine-grade, Douglas fir, 7-ply. Manufacturer: Roseburg				0.9235	0.1617	0.0325
A/B, marine-grade, Okoume, 11-ply. Manufacturer: Allin Bruynzeel					0.0207	0.0207
A/B, marine-grade, Larch/Fir, 7-ply. Manufacturer: Potlatch Marine Corporation						0.0061
A/B, marine-grade, Douglas fir, 7-ply. Manufacturer: Roseburg						

(green)	Not statistically significant
(orange)	Significant at the 0.10 level
(yellow)	Significant at the 0.05 level
(red)	Significant at the 0.01 level

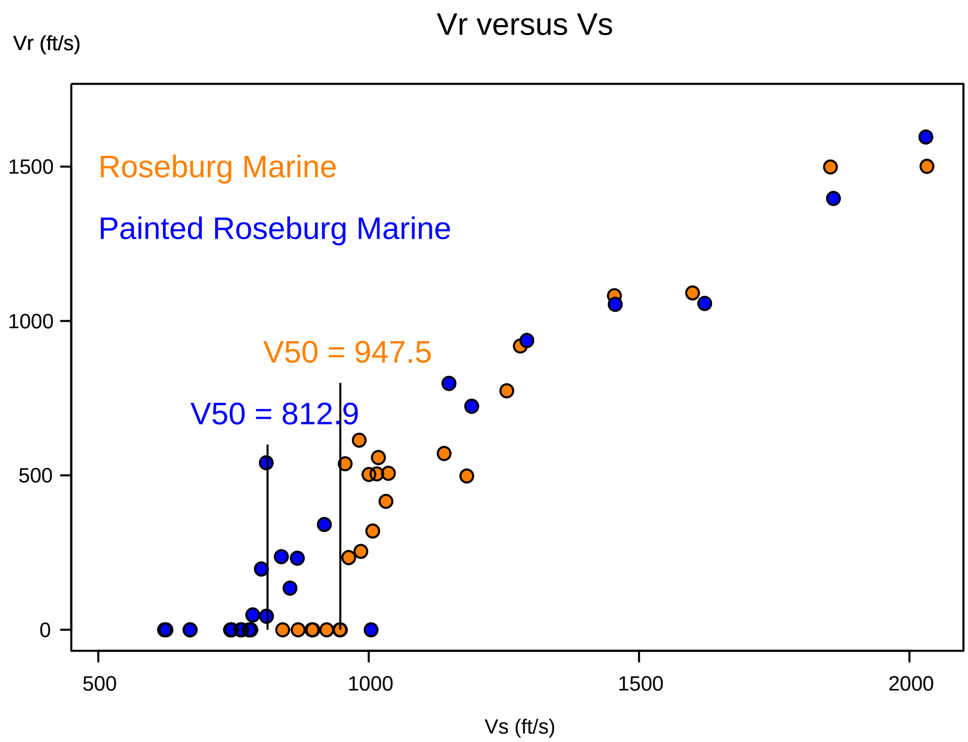

Fig. F-3 A comparison of residual penetrating velocities against 2 sheets of A/B marine-grade Douglas fir (7-ply) plywood (Roseburg), unpainted and painted

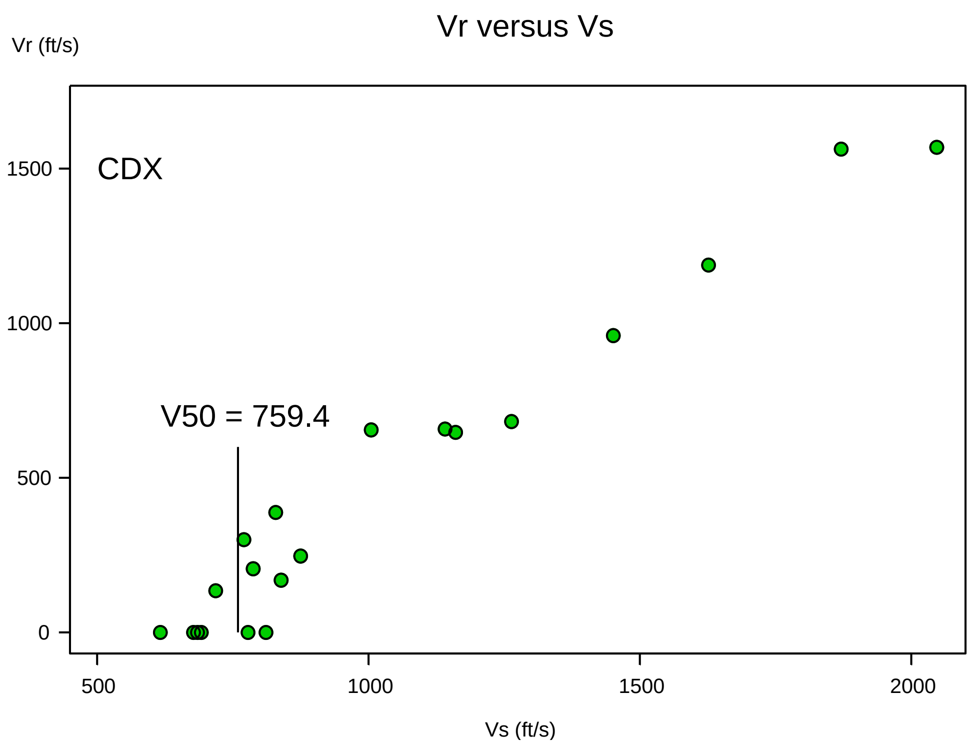

Fig. F-4 A plot of residual penetrating velocities for CDX, yellow pine, (5-ply) plywood (Georgia-Pacific)

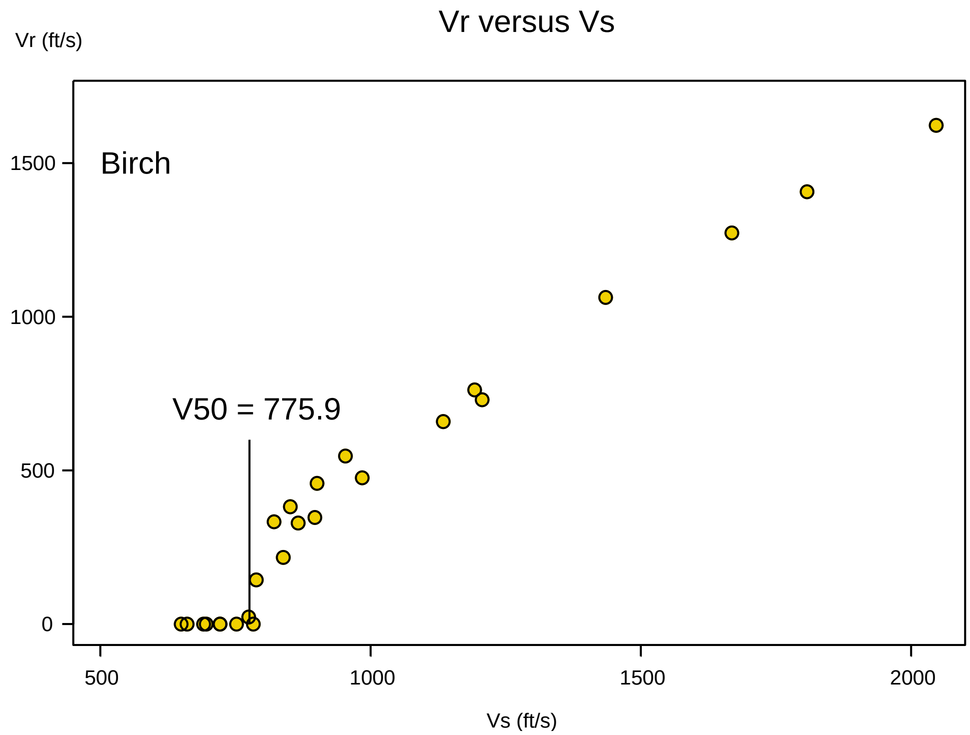

Fig. F-5 A plot of residual penetrating velocities for B/B, birch hardwood (11-ply) veneer-core plywood (Georgia-Pacific, China)

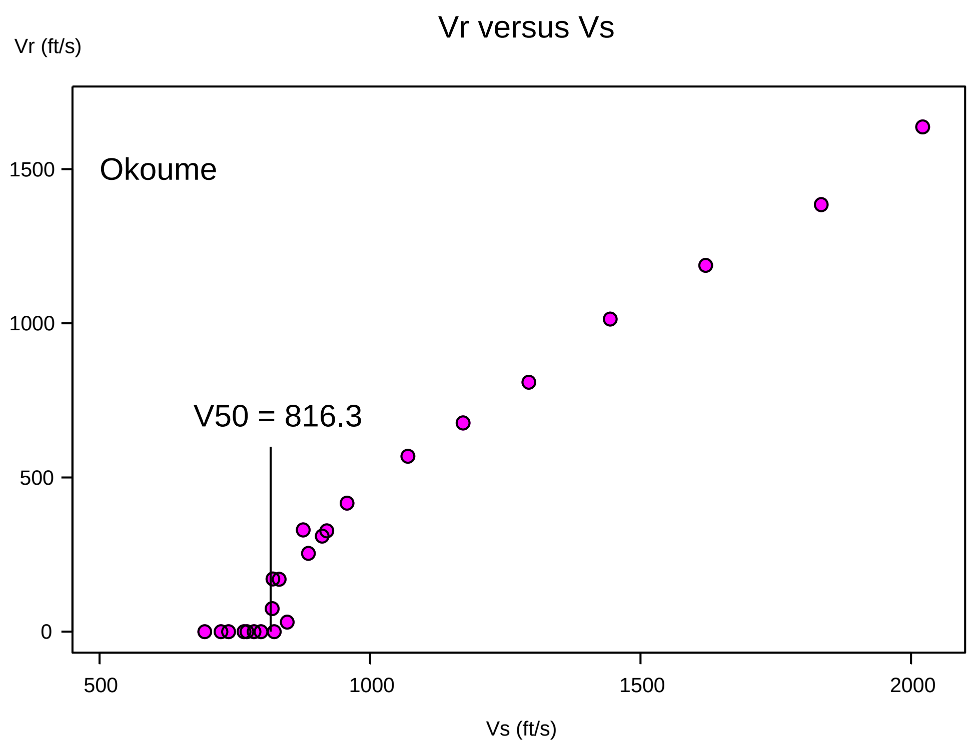

Fig. F-6 A plot of residual penetrating velocities for A/B, marine-grade, Okoume (11-ply) plywood (Allin Bruynzeel)

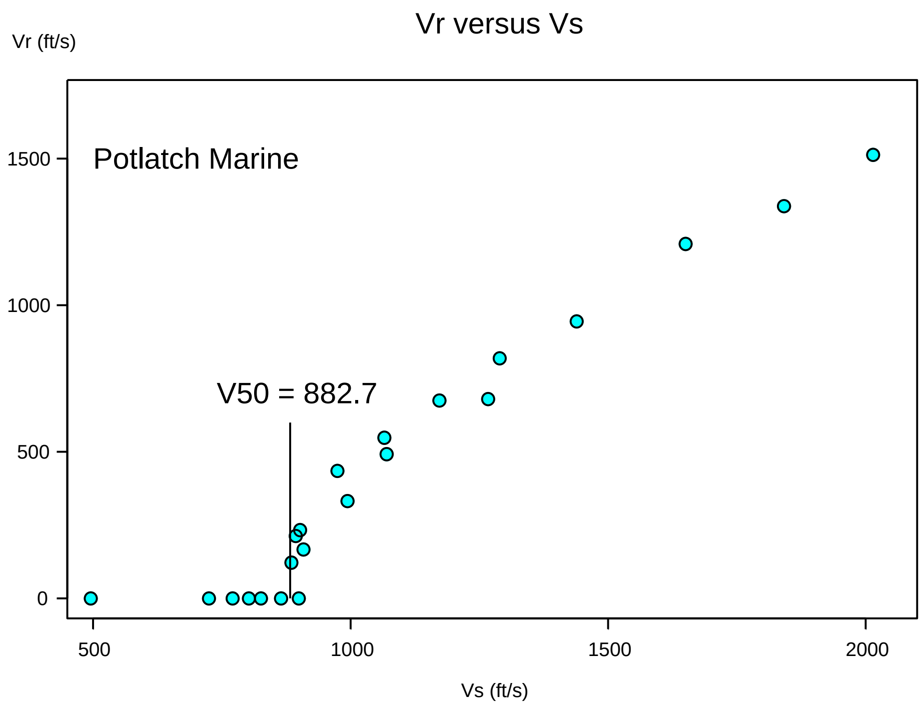

Fig. F-7 A plot of residual penetrating velocities for A/B, marine-grade, larch/fir (7-ply) plywood (Potlatch Marine Corporation)

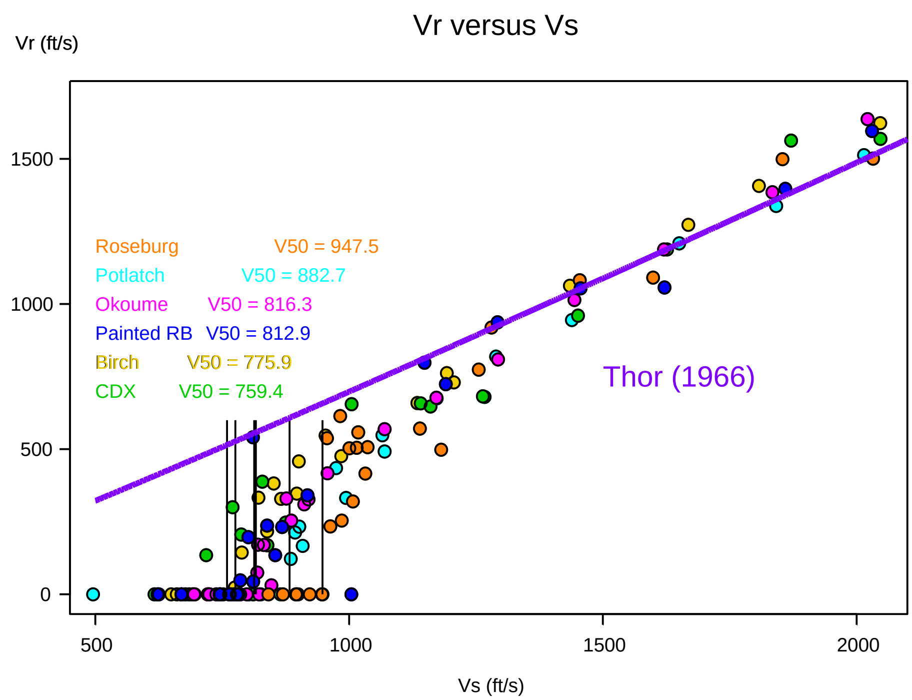

Fig. F-8 A plot of residual penetrating velocities for each type of plywood and the Thor equation[4]

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[4] Malick D. The resistance of various woods to perforation by steel fragments and small caliber projectiles. Aberdeen Proving Ground (MD): Ballistic Analysis Laboratory (US); 1966 June. Report No.: BRL-TR-62.

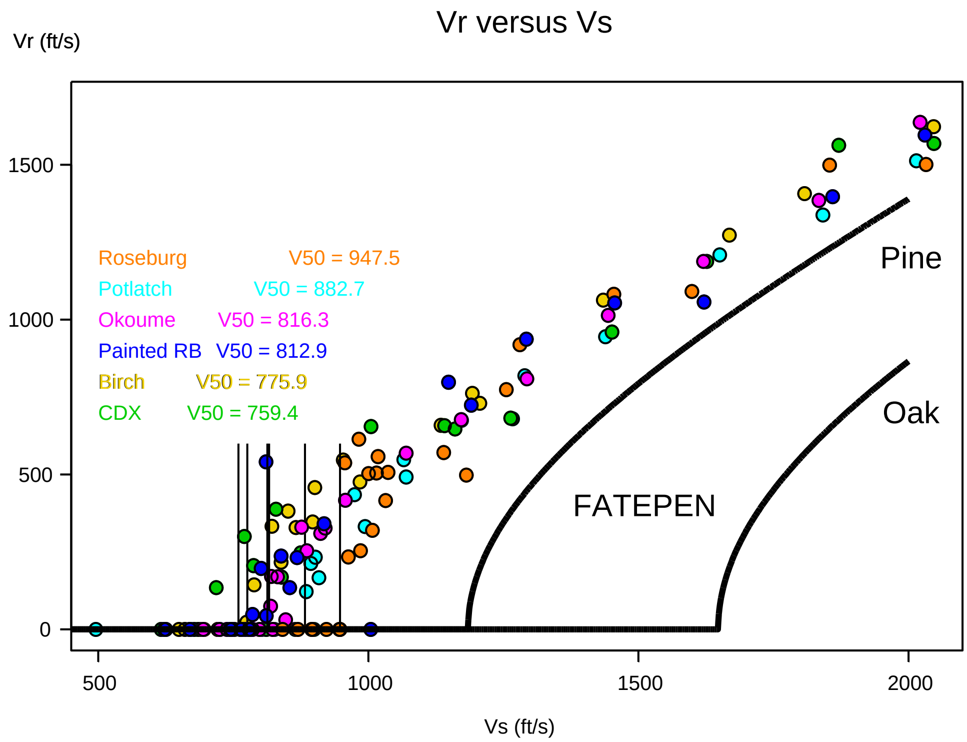


Fig. F-9 A plot of residual penetrating velocities for each type of plywood and the FATEPEN equations for pine and oak wood

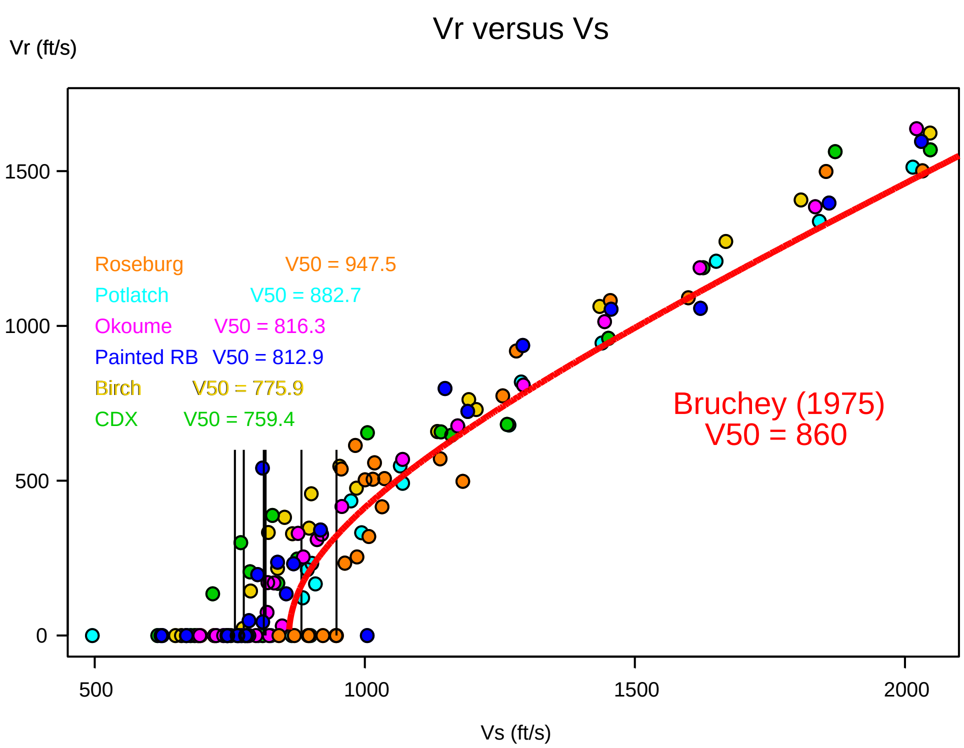
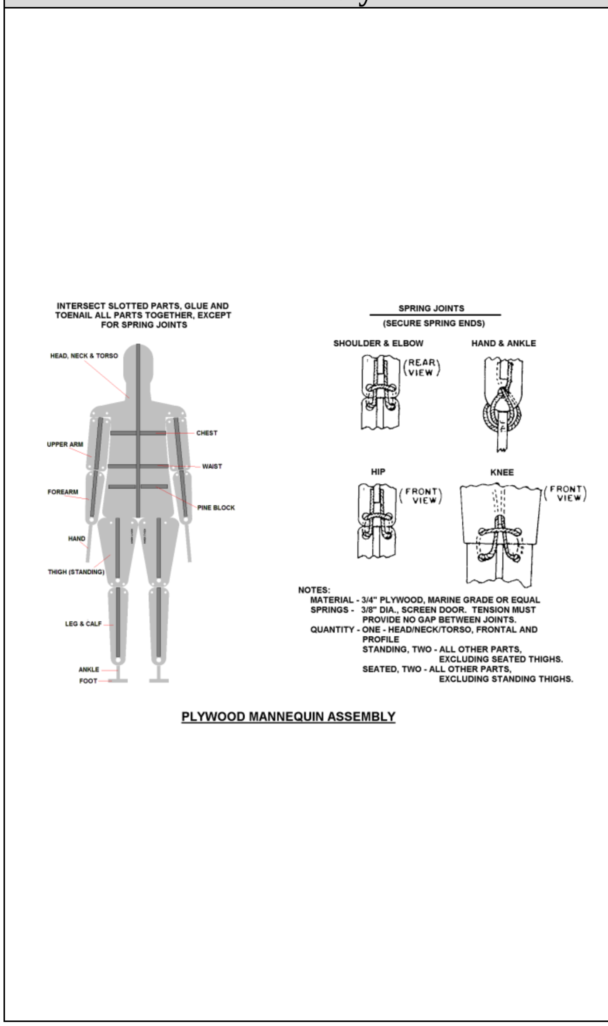


Fig. F-10 A plot of residual penetrating velocities for various plywood sheets and the Bruchey equation

Appendix G. Proposed US Army Research Laboratory Plywood Ballistic Mannequin

The drawings for 28 wooden components for the proposed US Army Research Laboratory (ARL) ballistic mannequin provide an alternative representative—a mannequin that is taller and larger than the older US Army Ballistic Research Laboratory (BRL) plywood ballistic mannequin (Fig. G-1). The hip is located to better accommodate the leg lengths of the seated and standing mannequin.

Assembly



Torso (Profile), 1 each

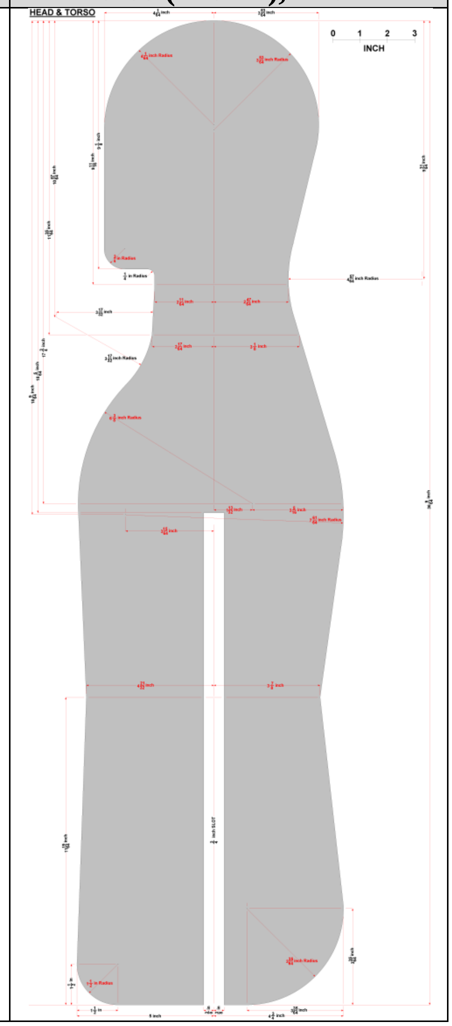


Fig. G-1 Drawings for the proposed ARL plywood ballistic mannequin

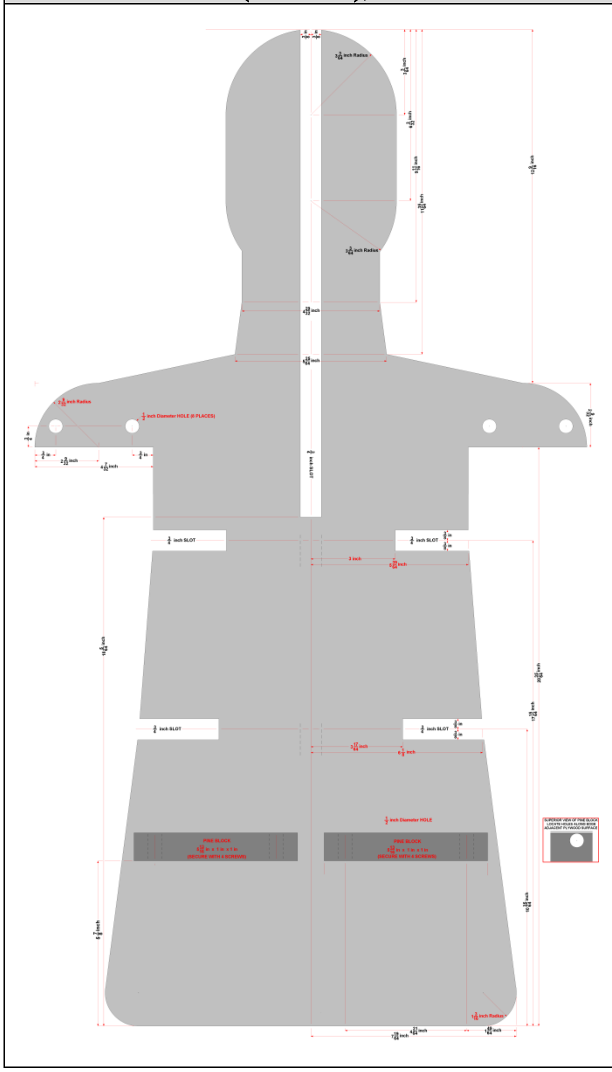
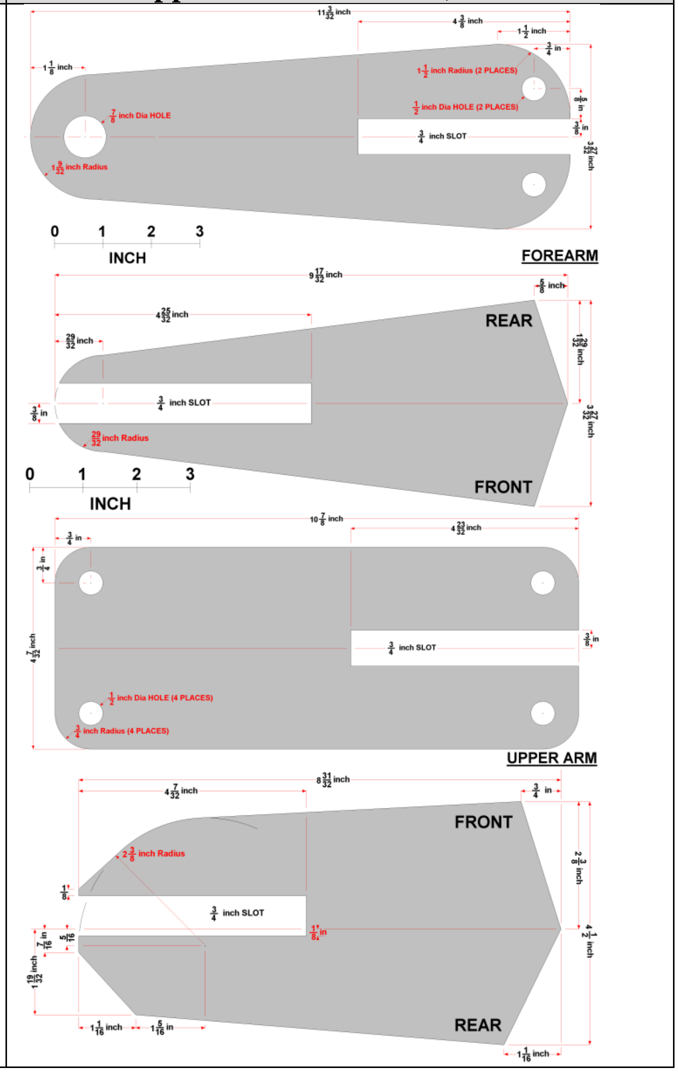
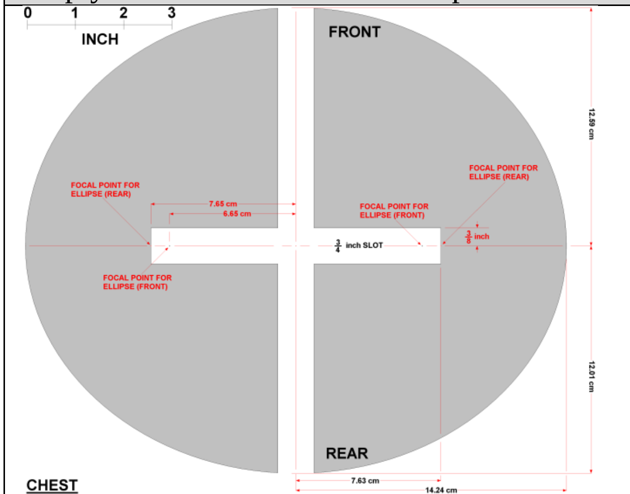
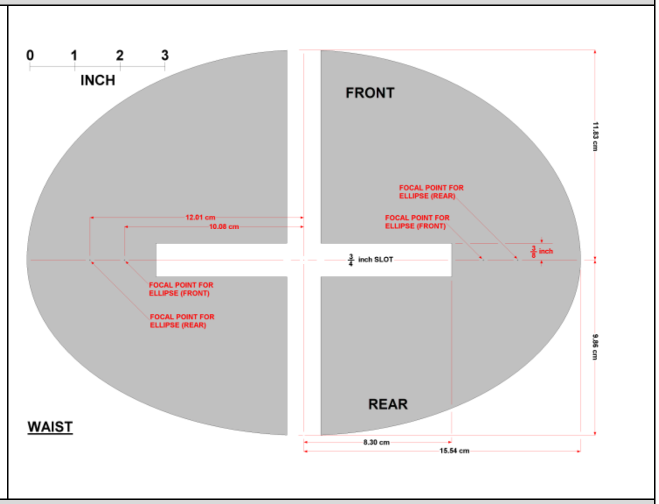
Torso (Frontal), 1 each	Upper and Lower Arm, 2 each
	

Fig. G-1 Drawings for the proposed ARL plywood ballistic mannequin (continued)

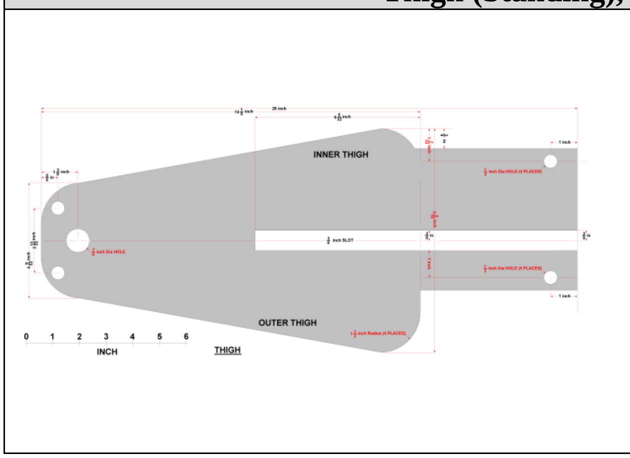
Chest and Waist, both halves

The right and left halves of the chest and waist components are drawn to show their contours are simply the result of 2 overlaid ellipses.





Thigh (Standing), 2 each (as required)



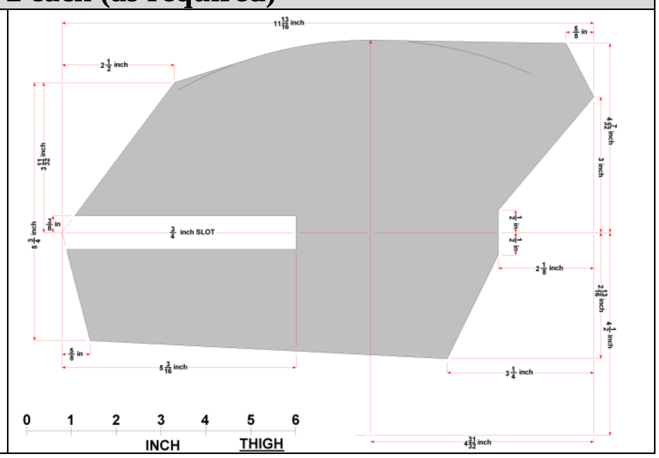


Fig. G-1 Drawings for the proposed ARL plywood ballistic mannequin (continued)

Lower Leg, Ankle, Foot, and Hand, 2 each

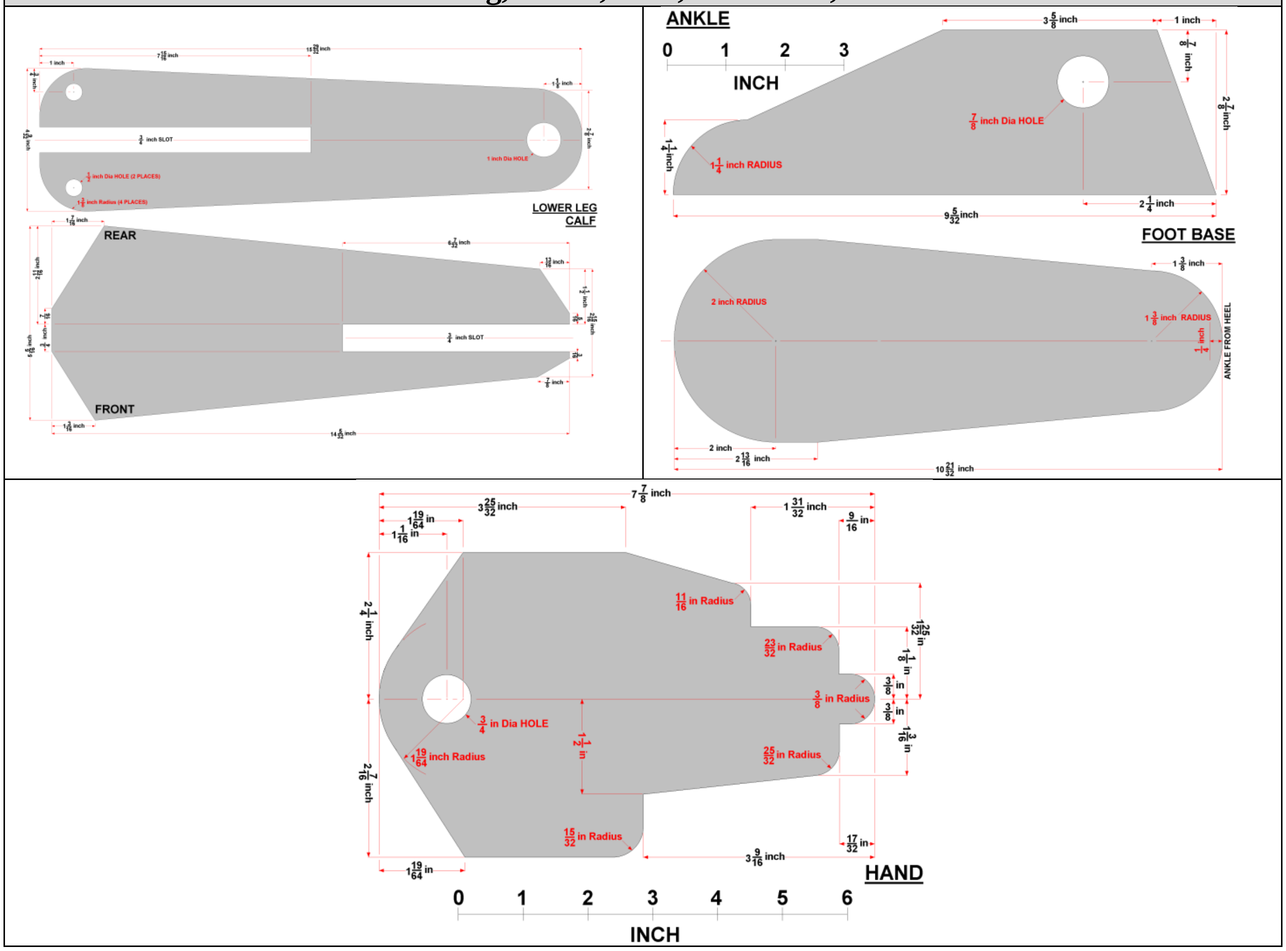


Fig. G-1 Drawings for the proposed ARL plywood ballistic mannequin (continued)

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Appendix H. US Army Ballistic Research Laboratory Plywood Ballistic Mannequin in Perspective

Although anthropometric dimensions individually, and in isolation, may appear to be reasonable, the data set of the US Army Ballistic Research Laboratory (BRL) mannequin is not representative of the US Army males.[1] Data cluster analyses, such as simple comparisons of 2 or more dimensions, can easily show that some physical dimensions of the ballistic mannequin are wrong, if the intent was to have a valid representative. Figures H-1 through H-7 confirm what we intuitively feel about the mannequin: the BRL mannequin is an outlier.

At even a cursory inspection of an assembled BRL plywood ballistic mannequin, Figs. H-4 and H-6 validate that the hands and reach are unusually long, giving it a simian-like appearance.

Rather than being located well within the 2-dimensional spaces, these data sets illustrate that the BRL plywood ballistic mannequin exists outside the space of the US Army male population. And, by extension, if a subset (or several subsets) of its data set is not representative, then the mannequin's data set cannot be representative, and the analytical product from its data set must be viewed with skepticism; similarly, if the data set is not representative, but the product can be independently determined to be representative, then the methodology must be viewed with cynicism. This is the Second Law of Analysis.[2]

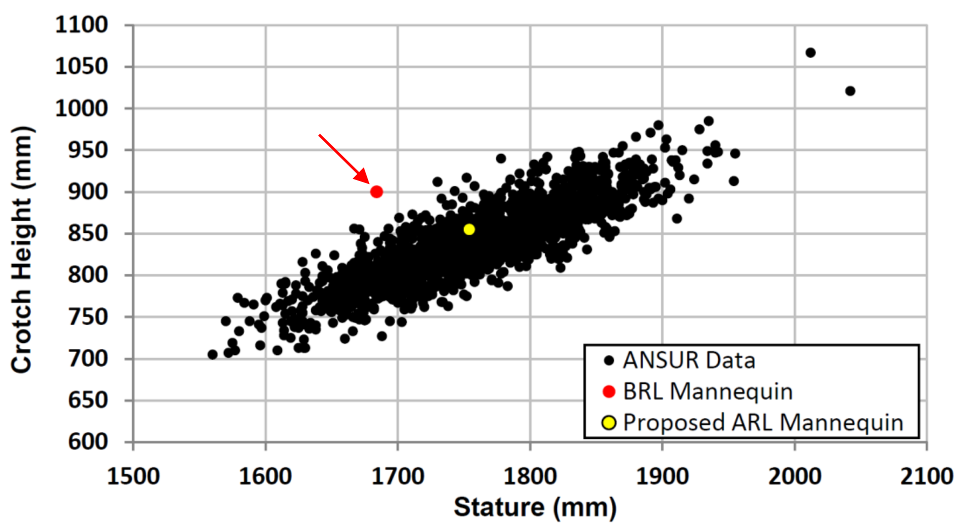

Fig. H-1 A simple comparison with the 1988 US Army Anthropometry Survey (ANSUR I) using 2 anthropometric doublets (stature and crotch height)

[1] 1988 US Army Male Anthropometry Survey. Human Systems Integration Information Analysis Center. [accessed 1998 August 8]. http://www.hsiiac.org.

[2] Kaufman M. Soldier survivability (SSv): volume II, sensitivity and specificity of ballistic targets for survivability and vulnerability analyses. 2nd ed. Silver Spring (MD): H-Bar Enterprises, Inc.; 2011.

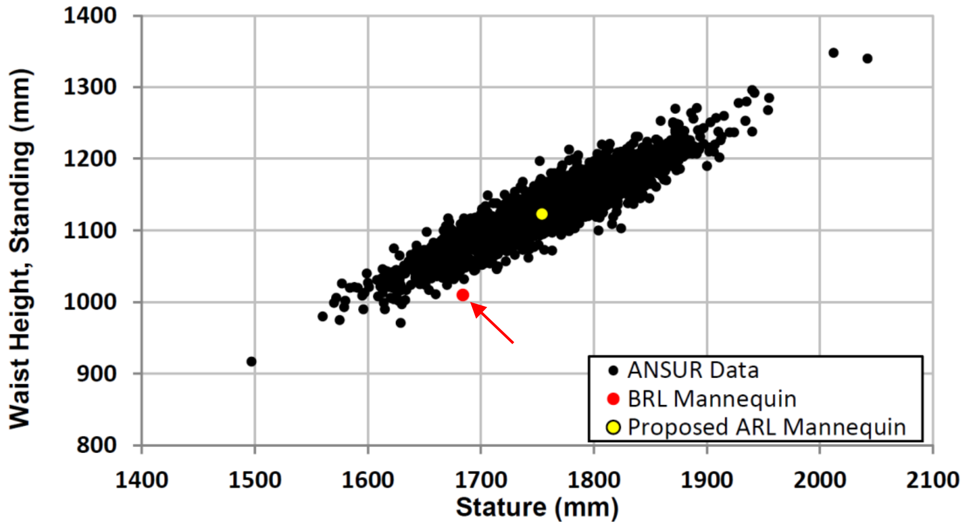

Fig. H-2 A simple comparison with the 1988 US Army Anthropometry Survey (ANSUR I) using 2 anthropometric doublets (stature, standing waist height)

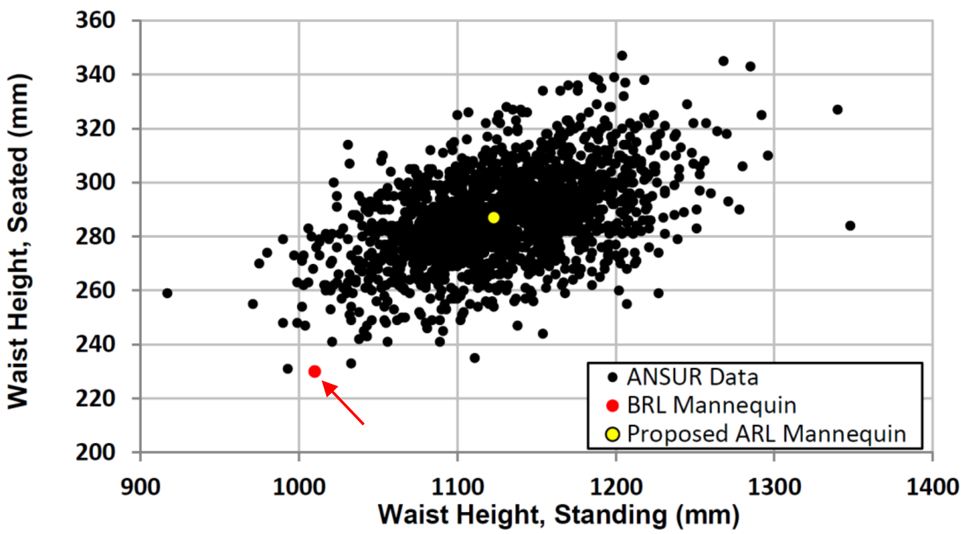

Fig. H-3 A simple comparison with the 1988 US Army Anthropometry Survey (ANSUR I) using 2 anthropometric doublets (standing waist height, seated waist height)

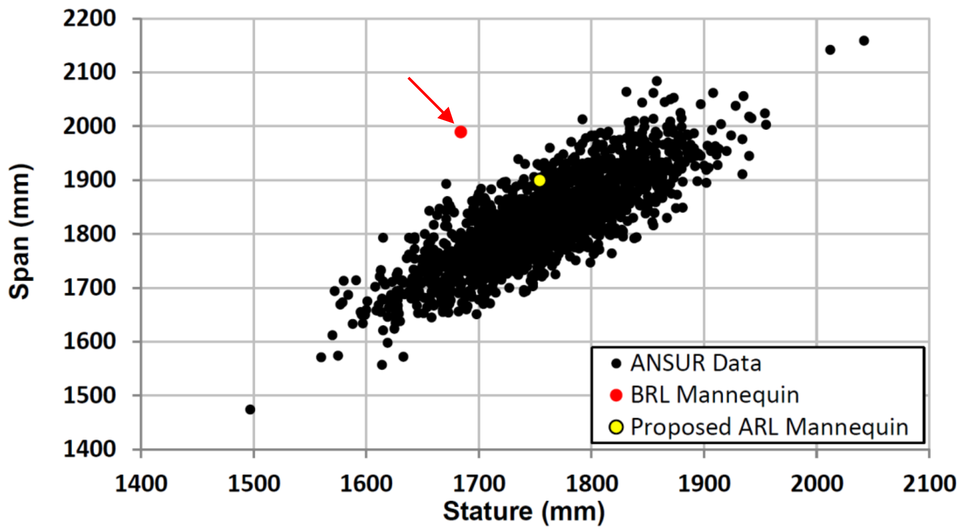

Fig. H-4 A simple comparison with the 1988 US Army Anthropometry Survey (ANSUR I) using 2 anthropometric doublets (stature, span)

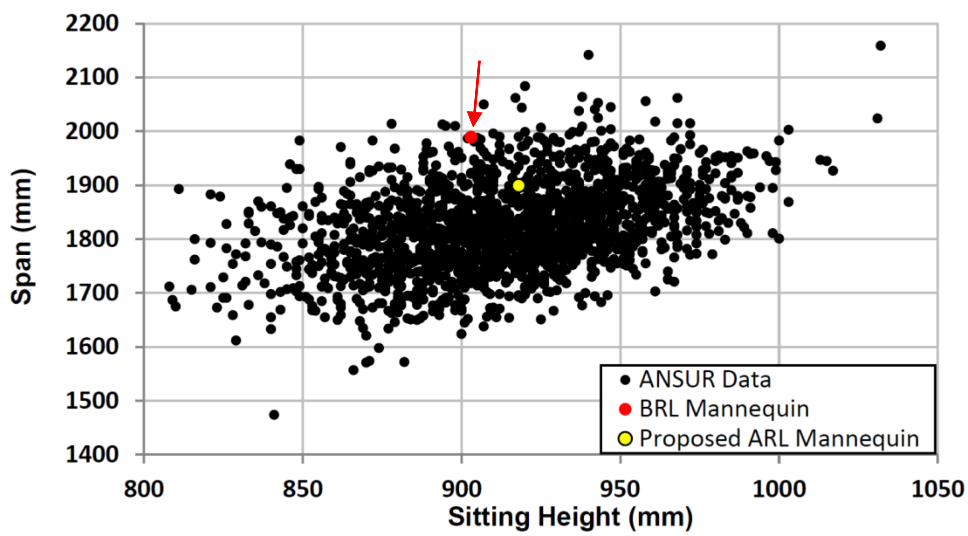

Fig. H-5 A simple comparison with the 1988 US Army Anthropometry Survey (ANSUR I) using 2 anthropometric doublets (sitting height, span)

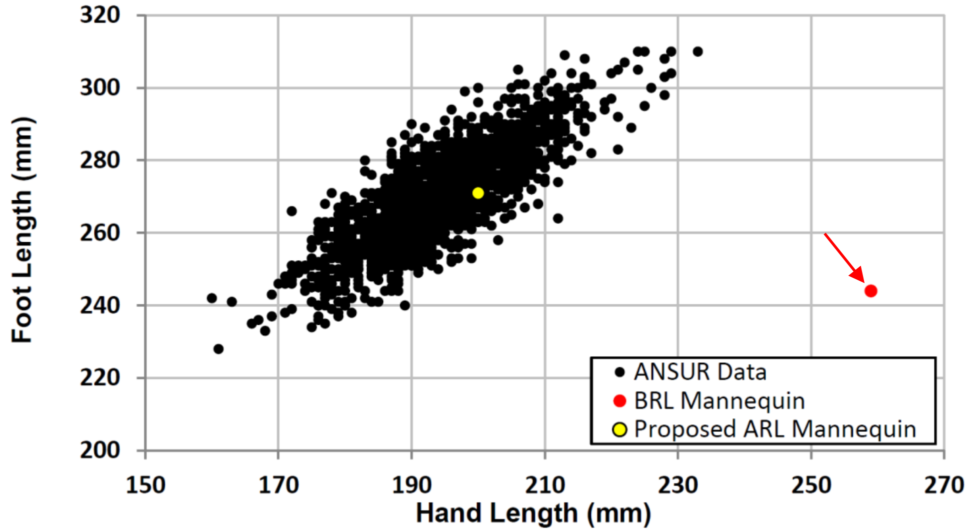

Fig. H-6 A simple comparison with the 1988 US Army Anthropometry Survey (ANSUR I) using 2 anthropometric doublets (hand length, foot length)

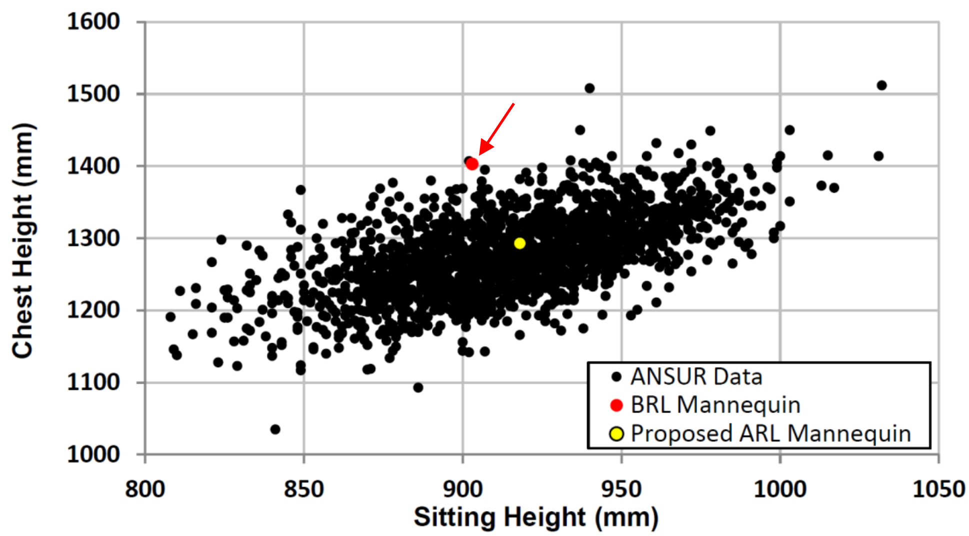

Fig. H-7 A simple comparison with the 1988 US Army Anthropometry Survey (ANSUR I) using 2 anthropometric doublets (sitting height, chest height)

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List of Symbols, Abbreviations, and Acronyms

APA	American Plywood Association
ARL	US Army Research Laboratory
ASTM	American Society for Testing and Materials
BPS	Bayesian probability statistics
BRL	US Army Ballistic Research Laboratory
BVL	ballistic vulnerability and lethality
CLUP	component location uncertainty probable
cm	centimeter
CP	complete penetration
G_d	dynamic shear modulus of plywood (pascal)
kg	kilogram
L	perimeter of fragment's presented area (meters)
LFT	live-fire testing
–LR	negative likelihood ratio
+LR	positive likelihood ratio
m	meter
M	mass of fragment (kilograms)
mm	millimeter
MOE	modulus of elasticity
m/s	meter/second
Θ	obliquity angle (degrees)
ORCA	Operational Requirement-based Casualty Assessment System
$P_{I/H}$	probability of incapacitation given a hit
PP	partial penetration
psi	pounds per square inch, lb/in^2

PVA	personnel vulnerability assessment
s.e.	standard error
SLAD	Survivability/Lethality Analysis Directorate
T	thickness of plywood (meters)
V_{50}	ballistic velocity of penetration with 50% probability (m/s)
V_{i}	impacting velocity of the fragment (meters per second)
V_{lim}	ballistic velocity limit of the fragment (meters per second)
V_{r}	residual velocity of the fragment (meters per second)
ρ	density of plywood (kilograms per cubed meter)

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